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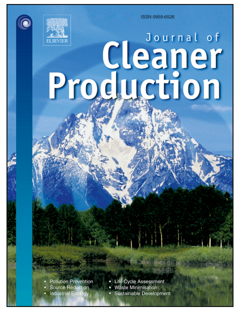

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PII: S0959-6526(18)30839-4

DOI: 10.1016/j.jclepro.2018.03.168

Reference: JCLP 12426

To appear in: *Journal of Cleaner Production*

Received Date: 13 September 2017

Revised Date: 15 February 2018

Accepted Date: 17 March 2018

How to better include environmental assessment in public decision-making: lessons from the use of an LCA-calculator for wastewater systems

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Abstract: Life Cycle Assessment (LCA), although widely disseminated in the industrial sector, remains underutilized in the public sector. The literature has addressed the relationship between scientific knowledge and decision-making from positivist and relativist epistemological perspectives. Both provide explanations for this weak dissemination and suggest solutions. Several of these solutions were explored through the implementation of a simplified LCA calculator in the public wastewater sector in France. This experiment highlighted the importance of two simplification principles: the first is to provide a calculator that already includes a catalogue of LCA ready-for use; the second is to guide the interpretation of LCA results by reducing, step by step, the number of impacts considered. A special effort has been made on the graphic format used to presents results. These principles can be generalized to other contexts. This work calls for the involvement of management sciences in LCA research and for co-building solutions with potential users.

Highlights:

- Obstacles to LCA use for public decision are identified and classified
- Solutions are proposed and discussed to overcome these obstacles
- One of the main obstacles concerns result interpretation
- Tests conducted show how much results presentation can affect decisions based on LCA
- Principles of simplification are implemented via a decision procedure and new graphs.

Key words: Life cycle assessment, public decision support, wastewater services, display of results

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1 Introduction

The importance accorded to the environment has steadily increased. There are a number of methods for environmental assessment (cost-benefit analysis, Environmental Risk Assessment, carbon footprint, water footprint...). Among these, Life Cycle Assessment (LCA) is the most comprehensive in terms of the environmental effects considered. LCA was formalized at the end of the 1980s and gave rise to an ISO standard in 2006 (ISO 14044). It is mainly being developed in the industrial world under the auspices of the Society of Environmental Toxicology and Chemistry (SETAC) and the United Nations Environmental Program (UNEP). Despite its success, its use remains relatively rare among public actors (Bidstrup, 2015) while other methods, such as Environmental Impact Assessment procedure, are used much more widely (Larrey-Lassalle et al., 2017). One hypothesis to explain this weak dissemination is that LCA remains a method difficult for non-specialists to appropriate.

This article examines the conditions for introducing LCA to support public decision-making in the case of investments choice (choosing between alternatives). Other uses of LCA (for instance eco-design or identification of the main contributors to impacts (Hellweg and Milà i Canals, 2014)) do not fall directly within the scope of the paper.

We explore the relationship between scientific knowledge and decision-making. First it questions the feasibility of integrating scientific information upstream of a decision, giving this information a form that renders it accessible, understandable and usable by public decision-makers. Then, the effect of this information on the decision actually taken is another issue that will be less developed in this paper.

The introduction of environmental assessment in public decision-making lead to three questions:
- What potential value of environmental assessment for public decision-making?
- What obstacles could explain its weak dissemination?
- What solutions could overcome these obstacles?

Answers can be found by using two epistemological positions: positivism and relativism. The first considers that scientific knowledge provides objective information that leads decision-makers to rationally optimize their choices. The second considers that scientific arguments, like other arguments, are in part socially constructed elements whose effects on choices depend on the people who use them and on the decision-making process.

In section 2 we present positivist and relativist perspectives on the relationship between scientific information and decision-making. We then look at what the literature can teach us about the potential of, and obstacles to the use of LCA by public decision-makers. This allows us to propose a typology of the difficulties and solutions identified.

Sections 3 and 4 present the experiment carried out to disseminate LCA in the public wastewater sector in France. We introduced a simplified LCA calculator that was developed to make environmental assessment accessible to non-LCA specialists. In response to persistent difficulties, the experiment led to design innovative solutions. The results confirm that the use of LCA by non-specialists in the public sector is possible under certain conditions. Improvements to make focus notably on facilitating the interpretation of quantitative results.

Sections 5 and 6 discuss the significance of our findings with regard to how scientific information from environmental assessment can be used for decision-making.

2 The relationship between science and public decision-making using an environmental assessment

2.1 Positivist and relativist perspectives

Efforts to understand the relationship between scientific knowledge and decision-making are dominated by two paradigms (Gezelius and Refsgaard, 2007). The first one, positivism, considers that choices are determined through rational reasoning that leads decision-makers to optimize their decisions based on objective and measurable information. The second one, relativism, considers that information is not absolute and that rationality is limited. The same information can assume different meanings depending on the individual who considers it. Various factors, which are not part of scientific rationality alone, also influence public decision-making.

These two perspectives don't give the same status to information in general and to environmental assessment in particular in public decision-making (Head, 2016). For rationalists, political decision-making can (and must) be based on scientific information. Decision is evidence-informed. For others, scientific information is only one of several elements to be considered and different kinds of determinants intervene (values, ideologies, economic interests, alliances). The link between political decision-making and scientific arguments then becomes weak to non-existent.

We will use these two paradigms to analyse the obstacles impeding the dissemination of LCA in local public decision-making.

2.2 Presentation of the local decision-making context

We are interested in public decisions made at the level of a local authority in charge of managing a territory, and not a national administration nor a ministry. This may be, for example, a municipality or a grouping of several municipalities within an inter-municipal association.

The notion of public decision-making we refer to involves several categories of actors related to a system of action. Gezelius and Refsgaard (2007) distinguishes elected officials (municipal council), who have the legitimacy of the vote and the power to make decisions, and technicians (administration) who have the legitimacy of skills and the power to advise elected officials. Consultants are also involved; they can (i) contribute to building projects (thus influencing the range of possible scenarios that will be subject to a choice) and (ii) support technicians and elected officials by contributing expert methods.

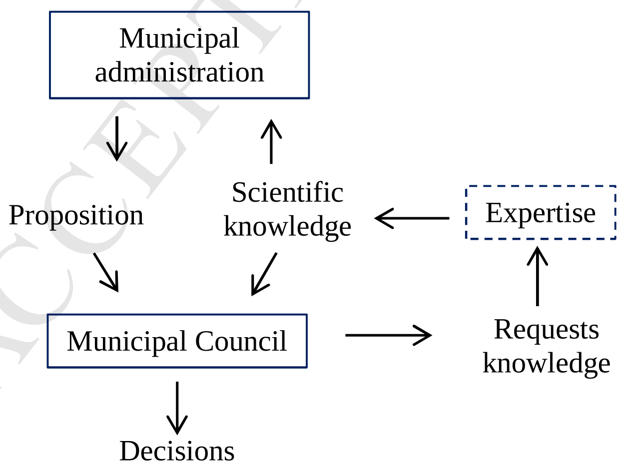


Figure 1 Decision-making procedure for wastewater treatment (adapted from Gezelius and Refsgaard 2007)

The context of our experiment is a choice of a technical infrastructure providing a clearly identified service (wastewater treatment) at the municipal level.

Typically, when a wastewater system is being chosen, none of the actors directly or indirectly involved in the decision is an LCA specialist.

2.3 Presentation of Life Cycle Assessment (LCA)

The LCA method quantifies the environmental impacts of a system (product, service, process) from the extraction of raw materials, through their transformation, use, and up to the end of the life of the system studied. Impacts are calculated for a "functional unit" that characterizes the service rendered. This is the unit of reference that makes possible, when appropriate, to compare several technical or organizational options rendering the same service. For a wastewater facility, for example, the functional unit can be the collection and treatment of effluents of one inhabitant over one day as proposed by Risch et al (2014).

The overall principle of LCA is summarized in Figure 2 and developed in Appendix A. For a detailed overview of the method, refer to the ISO standard (ISO, 2006) and to the scientific work developed by Jolliet et al. (2004). In a more recent article, Hellweg & Milà i Canals (2014) also propose a synthesis of emerging approaches in LCA.

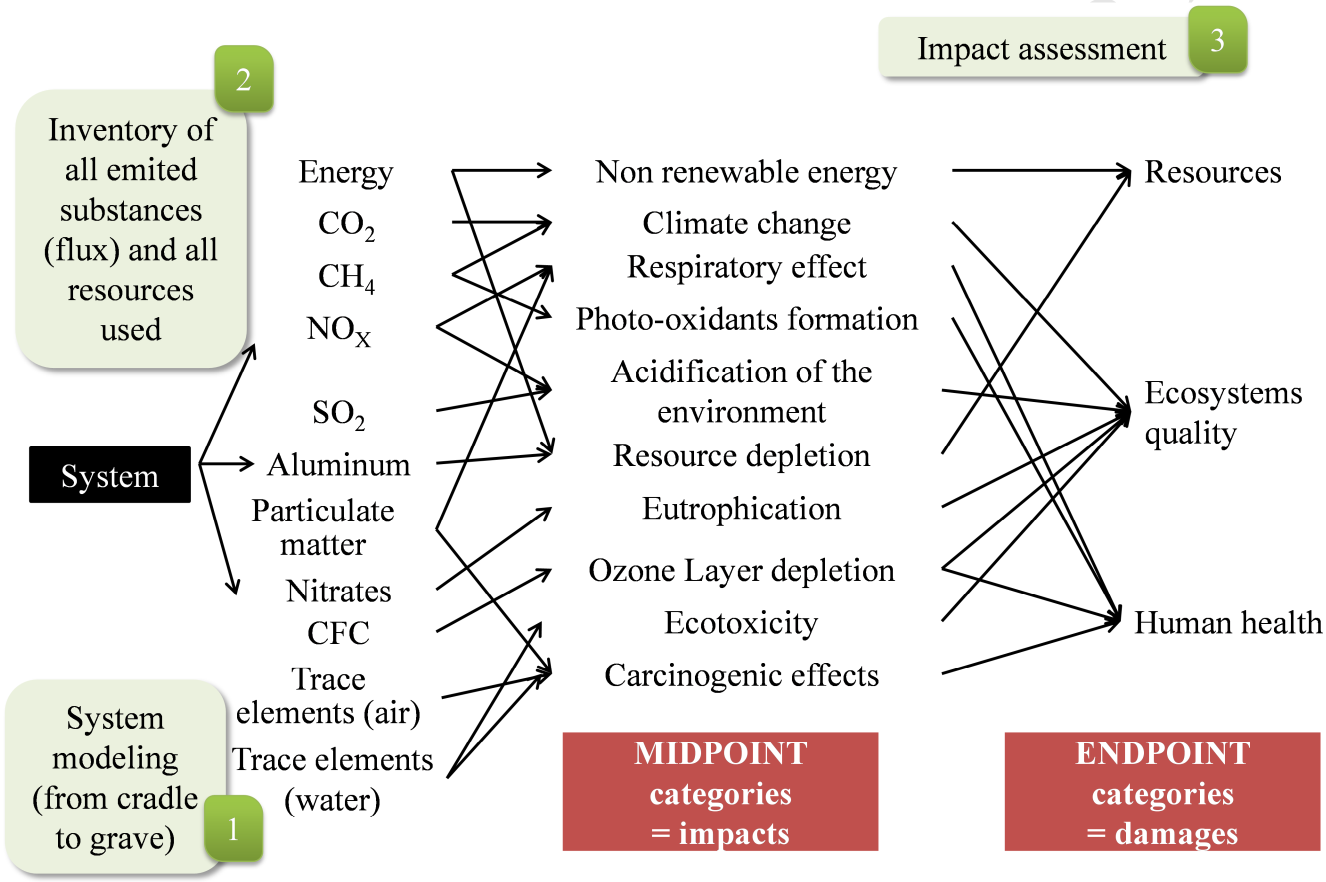


Figure 2 Overall structure of the LCA framework

Source: Philippe Roux and Laureline Catel, Irstea, 2014

The modeling of impacts and damages generally leads to a graphic representation of results. Figure 3 presents a standard representation that compares two options. It is the graphic format produced by a software commonly used by LCA specialists (Simapro). We provide this generic figure to highlight the simplifications we will propose for the graphic format in section 4.3.

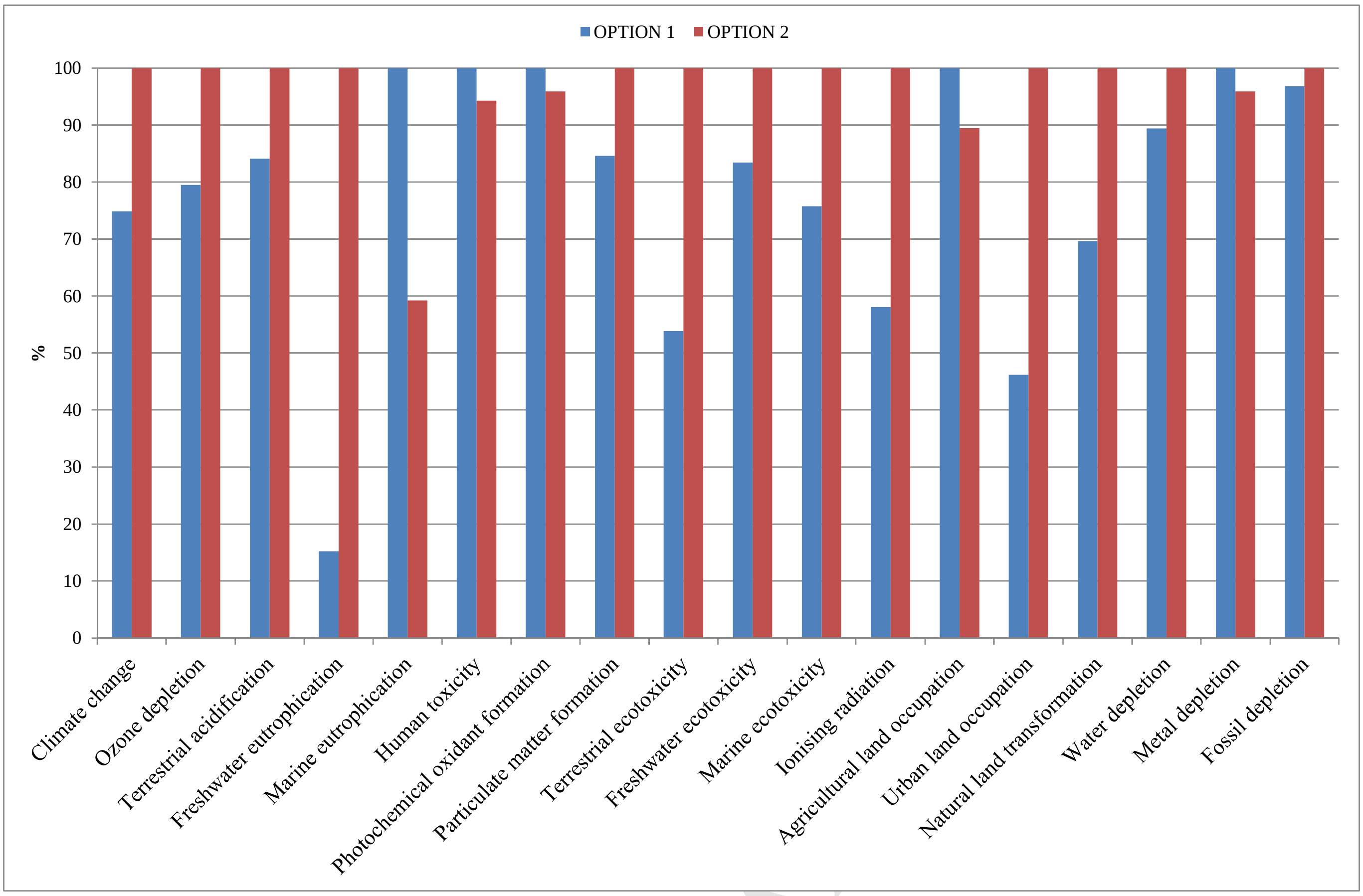


Figure 3 Example of a standard presentation of comparative LCA results (source: Simapro software)

The desire to account for all measured impacts leads to a multicriteria representation, with a comparison of the options for each of the midpoints. The comparison indicator is the relative difference between the options, represented by histograms. For each criterion (here midpoints), the impact level of the most impacting scenario is standardized to 100, the others being presented relative to this maximum. The same type of graph exists for endpoints.

In a global systemic vision, LCA intends to highlight pollution transfers between different impacts, locations or stages of the life cycle. It intends to enrich decision-making by not focusing exclusively on the impacts occurring on the observed site but by including all of the impacts induced around the world.

2.4 Introduction of LCA in local public decision-making

2.4.1 What value of LCA in public decision-making?

According to the positivist approach to decision-making, the main contribution of LCA is to provide quantified, complete and scientifically substantiated information to a decision-maker. This positivist vision predominates within the scientific and professional community of LCA specialists, which is dominated by specialists in process engineering and in the natural and life sciences (physics, chemistry, biology). As Riot (2014) points out, LCA professionals see the method as a tool for objectifying the environmental dimension, which renders a more rational management possible. LCA makes it possible to pass from intuition to quantification (Grisel and Osset, 2008) by incorporating the latest scientific knowledge available.

According to the relativistic approach, LCA has a much more discursive dimension. It helps to provide arguments to the person who uses it in front of other actors whom she or he must convince of the (environmental) soundness of a decision. The value of LCA is then not to provide a decision-maker information, but rather arguments that she or he can use before third parties. The implementation of LCA is seen as also conveying values which often are implicit for the user. Behind an apparent objectivity, methodological choices embody values, for example in choosing the time horizon of impacts or in the rules for presenting or aggregating the indicators presented (Freidberg, 2015 (on line)).

LCA can then be instrumentalized by choosing, for example, to present only some of the midpoint results or by proposing the functional unit which is the most advantageous for the person implementing the method. This practice includes greenwashing.

2.4.2 What obstacles impeding the implementation of LCA by public decision-makers?

We summarize the obstacles identified in the literature and through our own research by linking them to one of the two paradigms presented in section 2.1.

Positivism recognizes that public decision-makers do not automatically have access to scientific information:

- The scientific knowledge needed to understand the phenomenon being assessed may be inadequate or unavailable at a given moment. Furthermore, the data needed to conduct the assessment may be inaccessible. Then, the preliminary information required to conduct the assessment does not exist.
- Conversely, the scientific information available can be extremely sophisticated and on the cutting edge of science. This generates three obstacles: the cost of carrying out the assessment is prohibitive, there is a need for analytical skills that the public decision-maker does not possess, and there is a reluctance to learn from pilot programs (Head, 2016).
- Available scientific information may not reach its target (e.g., assessment report not read by decision-makers) (O'Hare, 1980).
- The timeframe for carrying out the assessment may be incompatible with the political agenda.
- Cognitive obstacles also exist. If information is too rich the human brain cannot synthesize it. The aggregation method can also create interpretation biases by implicitly weighting some indicators or by impoverishing the information transmitted. The way information is presented also can lead to biases and scientific information can be misinterpreted (Tufte, 1983).

Relativism identifies other obstacles: arguments based on scientific evidence are only secondary to all of the other factors shaping the decision:

- Public decisions are made in more complex contexts than in the private sector. There are multiple objectives (Bozeman, 2007) and it is hard to take all aspects into account in the assessment.
- Other dimensions may have a higher value than the environment (economic dimension, the satisfaction of citizens whose subjective expectations sometimes contradict scientific rationality) (Gezelius and Refsgaard, 2007).
- The institutional context (and in particular existing regulations) may hinder the use of scientific evidence (for example, if regulations require a less robust procedure or prioritize the indicators to be taken into account in a manner which is not compatible with the latest scientific models) (Laurans et al., 2013).
- Public decision-makers may not trust the scientific information produced. This effect is reported in particular for "black box" assessment tools where decision-makers must accept a result without understanding how it is produced (Baumann, 2000; Collins and Flynn, 2007; Schlierf et al., 2013).
- More cynically, policy makers may have an interest in slightly blurring the consequences of their decision to avoid being punished *a posteriori*. They may also fear that the environmental assessment may run counter to their *a priori* choice and refuse to take the risk of seeing their decision challenged (Berkhout, 1997). In the context of public management, vagueness and ambiguity may be desirable (Benzerafa Alilat et al., 2011).
- The scientific methods producing scientific assessments are generally designed with a supply-side logic. They do not necessarily take into account real decision-making needs (Laurans et al., 2013). In particular, LCA is denounced as a tool that is disembodied and too little contextualized (Grisel and Osset, 2008; Riot, 2014).
- For relativists, the fact that a decision is based solely on a supposed scientific truth is ultimately open to criticism: a good decision must take into account something other than scientific information, and in particular recognize the value of relevant professional expertise (Head, 2016). It then becomes difficult to assess the effects of the decision in view of the plurality of legitimate points of view (Cashmore et al., 2010).

Recent work on the dissemination of LCA confirms that several of these obstacles exist in the public sector (Schlierf et al., 2013).

2.4.3 How to resolve the obstacles to the use of LCA by non-specialists?

Aware of these limitations to LCA dissemination, several authors have examined how to make it possible for non-specialists to use LCA (Baumann, 2000; Berkhout, 1997; Bras-Klapwijk, 1998; Bras, 2011; Cashmore et al., 2010; Collins et al., 2009; Collins and Flynn, 2007; Guérin-Schneider and Tsanga Tabi, 2017; Head, 2016; Heiskanen, 2002; Laurans et al., 2013; Maiello et al., 2015; Moss et al., 2009; O'Faircheallaigh, 2010; O'Hare, 1980; Petts, 2000, 2004; Theodosiou et al., 2015; Van Hoof et al., 2013).

Some recommendations are to be implemented before an LCA is conducted (institutional framework, decision context…). Others concern the content of the LCA method (evaluation methods, reduction of the complexity…). Lastly, others concern the evaluation process (transparency, intermediation…).

Referring either to the positivism or relativism, we propose a typology of obstacles and recommendations for the use of LCA in a public context (Figure 4).

We explored several solutions in our experimental approach. However, the solutions are not all necessarily compatible or legitimate in everyone’s eyes. We deliberately set aside certain options addressing the difficulty posed by the multicriteria dimension of LCA.

We dismissed the use of multicriteria decision analysis (MCDA) methods. Such methods (Roy and Vanderpooten, 1996) aim to resolve the difficulty of making a decision with a large number of criteria by modeling preferences. We excluded it because:
- MCDA adds to the black box effect by applying a second layer of mathematical models,
- for LCA experts, the current state of scientific knowledge does not render it possible to rank categories of impacts between them,
- LCA non-specialists involved in the field-test were unable to express preferences.

We also refuted reducing the number of indicators presented to a subset reflecting the most significant issues for the given context. It calls for an *a priori* expertise that cannot necessarily be generalized from one sector to another. It also involve a risk of reductionism and carry hidden values (Schlierf et al., 2013).

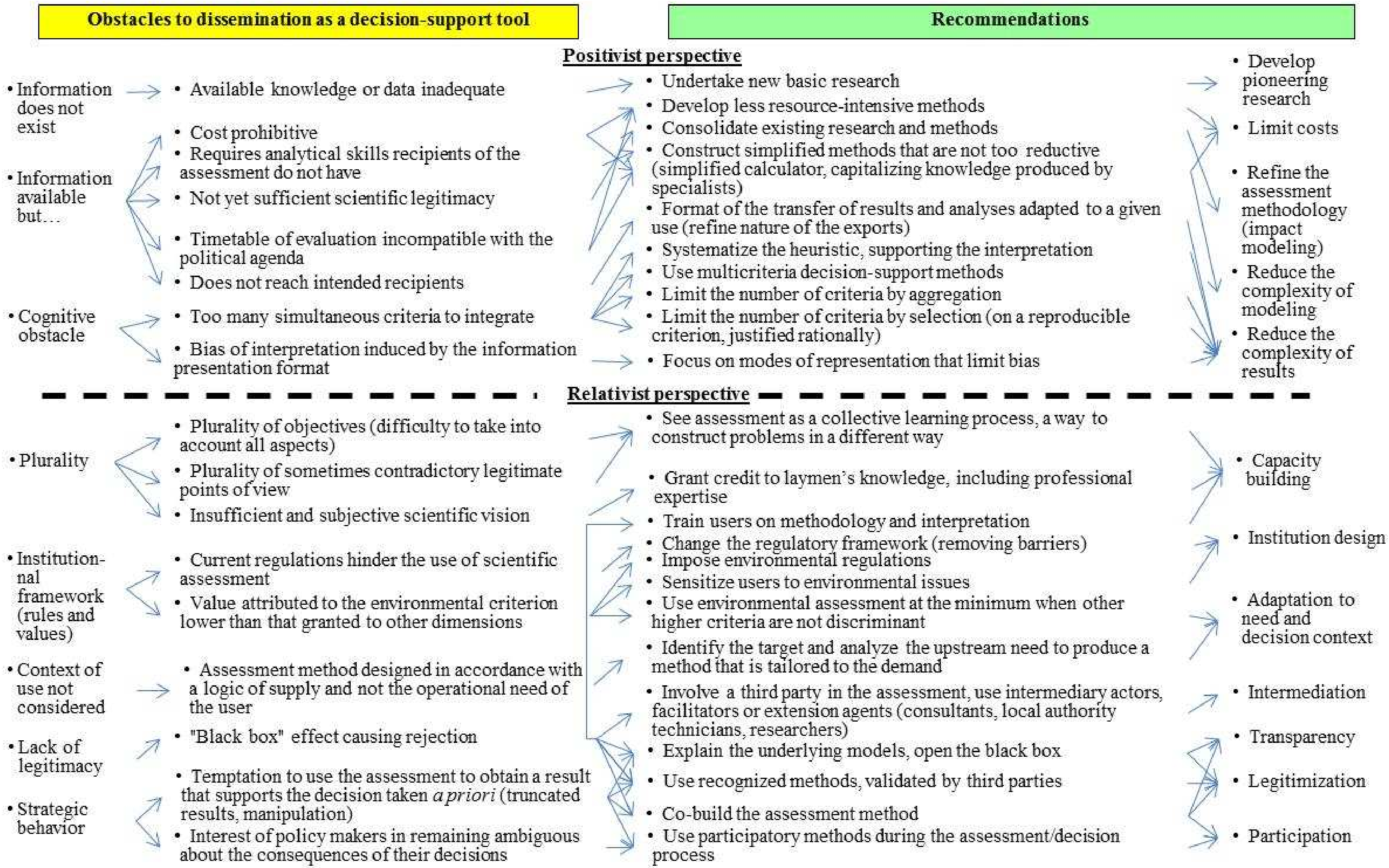


Figure 4 Typology of obstacles to the dissemination of environmental impact assessment in public decision-making and recommendations for overcoming them

3 Field and method: an intervention-research in French sewerage utilities

3.1 The interest of LCA in the wastewater sector in France

Because the wastewater sector intends to protect the natural environment, it is particularly relevant to use LCA. However, the dissemination of LCA in France is still in its early stages. Some studies have proposed LCA models for sewerage treatment systems (Foley et al., 2010; Risch et al., 2015), but information on their application in the field is still lacking.

In France, sewerage services are the responsibility of local authorities (municipalities or inter-municipal syndicates). Municipalities can choose to operate the service themselves or entrust it to a private operator. The local authority will generally remain responsible for the main investments. The major French water companies (Veolia and Suez) have been interested in LCA for several years. However, local authorities have not yet or rarely use it.

3.2 Presentation of ACV4E: a simplified calculator for public sewerage services

Two of this article's authors developed in 2015 a preliminary version of a simplified calculator to support investment decisions in the wastewater sector. This software, named ACV4E, aims to disseminate LCA in local authorities by making it easier for non-specialists to use. ACV4E and the underlying model have been presented in specific scientific articles (Risch et al., 2015; Risch et al., 2014; Risch et al., 2012) and in a website[1].

This work produced a database of wastewater treatment plants and sewer networks whose impacts had been assessed previously with an expert LCA software (SimaPro). This allows ACV4E user to set up a complete sewerage system combining one or more sewer networks and one or more small to medium-sized wastewater treatment plants. The user also can personalize numerous parameters by:
- modeling different scenarios (complete or partial wastewater systems) from the basic blocks made available,
- parameterizing the operation of each system according to the particular conditions the user wishes to simulate (for example, a required discharge level, an expected amount of pollution),
- producing the results of the LCA analyses of the scenarios built and parameterized in order to compare these scenarios and then interpret these results to clarify an investment decision.

3.3 Field experiment

We followed the intervention-research protocol (Hatchuel, 2000; Moisdon, 1984): the introduction of a new tool by the researchers rendered it possible to observe the changes induced in the organization and in decision-making.

The pilot experiment brought together 6 municipalities or inter-municipal structures, responsible for sewerage services, a departmental council and two consulting firms providing technical support on wastewater systems. (See Appendix B for a full description of the participants).

The experiment was conducted in two phases between 2013 and 2016. First, the software ACV4E was transferred to the local authorities so that they could use it on a real case in their wastewater service. This first phase not only tested if the transfer was feasible, it also identified more precisely users' needs (which question do they wish to address and what tools are needed to do so) in order to improve the technical content of the tool. Then, a specific work was carried out to improve the presentation of LCA results, and thereby the interpretation made of them.

[1] Link to ACV4E software website (in French): https://acv4e.irstea.fr

4 Results: LCA appropriation by pilot local authorities

4.1 LCA uses observed

The local authorities were asked to use the software to clarify investment decisions involving their sewerage service. Some chose to use LCA on equipment decisions in process, others on decisions already made to verify *a posteriori* their environmental relevance.

The time dedicated to the initial ACV4E training and then to the simulations and data entry of the scenarios remained reasonable and compatible with the workload of agents (from 1.5 to 4 days).

In the largest local authorities, the software was used by technicians from the sewerage service, and the results were presented to department heads and other interlocutors when appropriate (Departmental Council, water agency). In the smallest local authorities, the software was used either directly by the head of the service or by a technician under his or her command. The LCA results were presented only once to elected officials involved in decision-making; none were presented to any users or consumer associations. This was a deliberate choice of the local authority technicians who esteemed that they had not adequately mastered the interpretation of LCA results to present and discuss them with elected officials. This major difficulty gave rise to a specific development in the second phase of the experiment (see 4.3).

The experiment revealed a potentially wider use than that originally intended (investment choice) (Table 1).

Table 1 The uses emerging from the ACV4E experiment

Types of LCA use envisioned by the local authorities	
Investment choice	Comparison of different facilities possible prior to an investment policy decision
Eco-design	Comparison of several technological variants (the choice of the type of facility already having been made) prior to the design of equipment
Eco-exploitation	Comparison over time of the environmental impacts of existing equipment (inter-annual monitoring)
Process benchmarking	Compare the environmental impacts of several existing facilities to a reference

4.2 Upstream improvement of the software: scenario modeling

During the experiment, the software evolved to meet users modeling needs:

- New functionalities and improved interface: the initial database was restructured for more intuitive use; the vocabulary used was adapted to the field; "information bubbles" were created to improve understanding; the parameterization of scenarios was refined.
- New elements in the database: new treatment systems were added ; new micro-pollutants were introduced as well as various additions (materials, reagents, electricity).

4.3 Downstream improvement of the software: display of results and interpretation procedure

4.3.1 Initial version

The initial version of ACV4E, developed (in French) included a relatively basic module for the use of results.

It only provided a graph that could be exported as an image (see Figure 5). No export of the numerical data corresponding to the graphs was possible.

These graphs presented the results in a classic LCA format (like those provided by classical LCA software, see Figure 3). For each midpoint or endpoint, the user was also able to view the specific contribution of certain sub-stages of the life cycle or of system components.

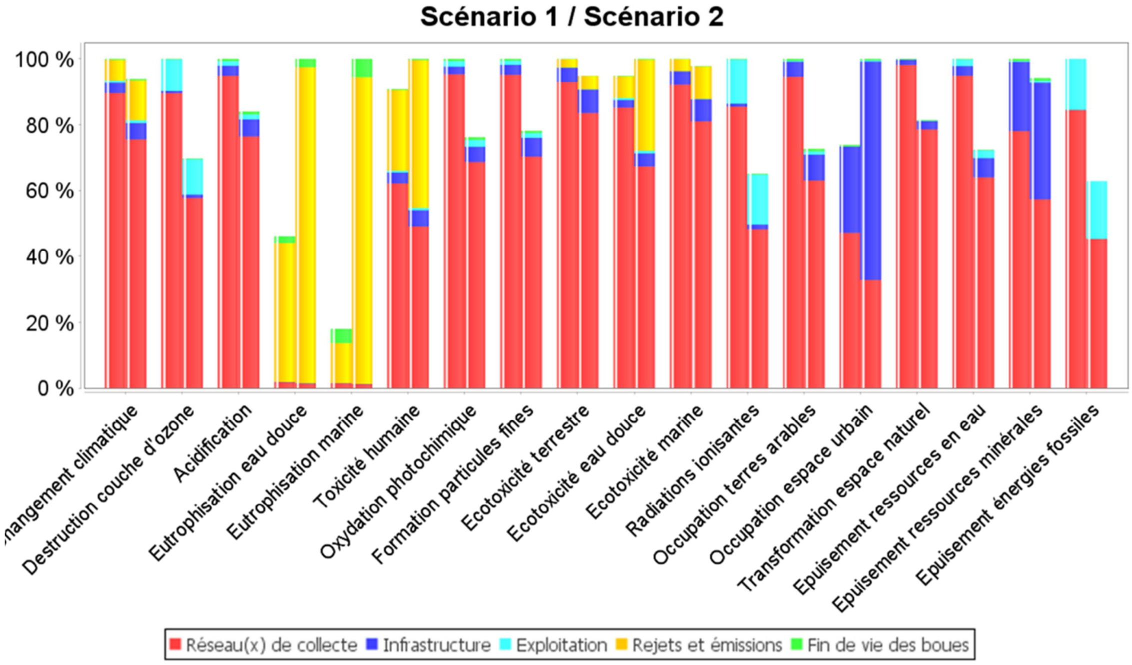


Figure 5 Example of the display of the comparison of midpoints for two scenarios as produced in the <u>initial version</u> of ACV4E before the test with the users (screen shot, in French in the original version of ACV4E)

This classic LCA display is based on principles that can lead to a poor understanding of the results by non-specialists:

a) The comparison of scenarios is based on relative differences between the impacts of each scenario without taking into account the magnitude or severity of the impacts; all of the impacts implicitly have the same "weight".
b) The absolute value of the impact may be very low, despite a significant difference between scenarios.
c) It is difficult to take into account all of the information contained in this graph (18 impacts differences) to make a comparison and a choice.
d) The representation provides twofold information: a comparison of two scenarios, but also the contributions of the main items to each impact.

As an option, initial ACV4E version also could display normalized results, i.e., expressed in relative terms with reference to the impact of an average European citizen. Normalization is a standard method meant, in theory, to facilitate LCA interpretation: the impacts of the systems studied are divided by the impact of one European citizen over a year, meaning by the pollution generated by all of the activities of one person living in Europe over the course of one year. What is difficult for a non-LCA specialist to understand is that if a normalized impact has a high value, this provides no indication about the severity of the impact. It simply means that the system studied contributes significantly in the pollution generated by a citizen, for this type of impact. One of the questions asked during the field experiment was whether the use of normalization, which is not completely intuitive, would facilitate the task of interpretation for non-specialists.

4.3.2 The changes considered

By analyzing recommendations in the literature concerning how to display data (Bertin, 2013; Tufte, 1983), and in an attempt to address the difficulties of interpretation observed in the preliminary phase of the field-experiment, we developed several strategies to improve the presentation and interpretation of results.

A first option (graphic simplification) consisted of improving the form of the graphs presenting the midpoints and endpoints. This consists of eliminating "graphic noise" and reinforcing informative ink (Tufte, 1983) by removing visual artifacts interfering with the reading of information (especially volume effects and brightness, as well as the palette and strength of colors in Figure 5).

A second option (cognitive simplification) was to develop and propose principles to reduce the complexity of the information transmitted and to guide the reasoning leading to a choice. This step is based on limiting the number of criteria or scenarios by following logical principles which can be applied to any scenario and are explained during the procedure.

These two strategies led to two types of improvement in the software:
- introduction of new graphs to present midpoints and endpoints;
- introduction of a decision tree (predefined procedure of choice by step) making it possible to structure the decision by proposing explicit simplification modalities.

Both improvements are linked: the decision tree procedure uses the new graphs.

For the particular case in which only two scenarios are compared, specific graphs were proposed to make them easier to read and understand, compared to the conventional displays using histograms.

Table 2 presents all of the principles of simplification and/or clarification that were used. The fourth column provides references to the graphs used during the test, applying these principles. The comprehensive list and the coding of the names of graphs tested, mentioned in this column is detailed in Appendix C (see Table C. 2).

Table 2 Principles of simplification and/or clarification used in the new displays and in the decision tree

Code	Principle	Purpose	Representation / procedure applying this principle during the test*
P1	Use both midpoints and endpoints (to verify the convergence between the two levels)	Consolidate the validity of the comparison	Decision tree (DT) H6 H6V
P2	Rank the midpoints in descending order of impact on one of the scenarios	Increase readability for easier comparison	H3 H3V H4 H4V
P3	Highlight the criteria where a scenario dominates the others, dedicating one color to each scenario	Increase readability for easier comparison (by insisting on the number of times one scenario is the best)	H3V H4V
P4	Use the normalized graphs	Provide a reference for easier interpretation	None
P5	Adopt a pedagogical presentation with a two-armed balance symbol to present the dominances between scenarios (applicable to compare 2 scenarios exactly)	Facilitate understanding of results using a more intuitive notion	H9
P6	Presenting the comparisons in proportions "A is twice as impacting as B" rather than as a percentage of the most impacting ("B represents 50% of A)" (applicable to compare 2 scenarios exactly)		H10
P7	Discard midpoints whose damage** is negligible compared to that caused by other midpoints (i.e., damage 100 times less than the greatest damage caused)	Limit the number of criteria by removing the least relevant	H4 H4V
P8	Discard the criteria where the difference between scenarios is not sufficiently discriminant		H5 DT
P9	To eliminate the criterion or criteria already subject to environmental regulations (it is assumed that in complying with regulations, the impact will be at a level that can be tolerated by the environment) (applicable to the two criteria concerning eutrophication)		DT
P10	Use a subset of midpoints selected by the LCA experts for wastewater systems which they modeled in the software		DT
P11	Use a subset of midpoints selected by decision-makers (elected officials and/or local authority technicians) based on the issues they consider important		None

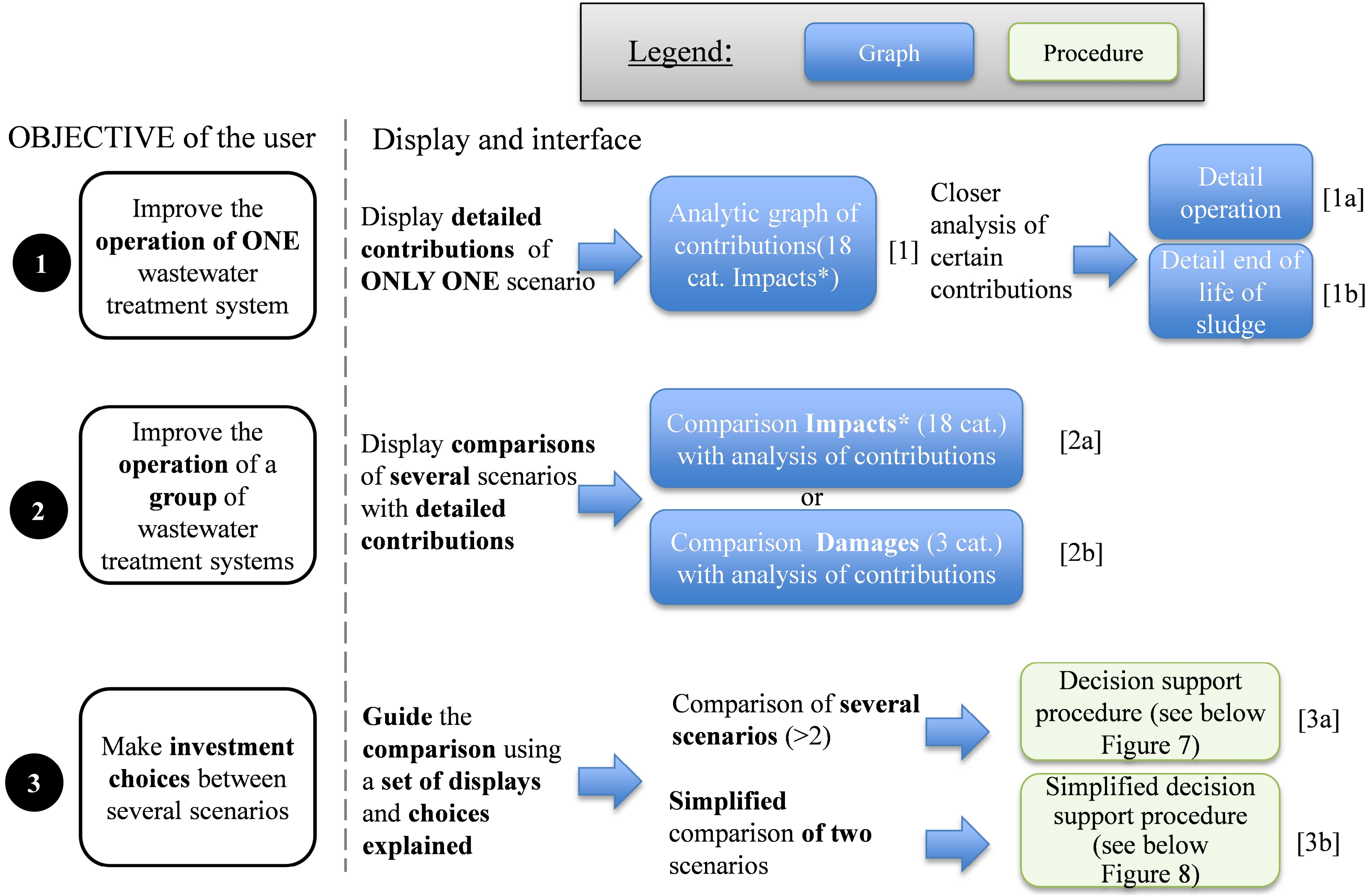
* See Appendix D for the complete presentation of the graphs.
**Damages are expressed in endpoints unit (when applicable).
Note: Graphs H1, H2, H7 and H8 are conventional unmodified presentations of ACV (midpoint and endpoint results for 3 and 2 scenarios respectively). They do not correspond to any simplification and consequently are not included here.

A test has been conducted involving both operational partners, LCA specialists who developed ACV4E and researcher in decision sciences to assess the pertinence of the changed considered in Table 2 for improving interpretation and use of ACV4E results. The detailed conduct of the test is presented extensively in appendix C, and D.

4.3.3 Proposal for a new interpretation-support procedure

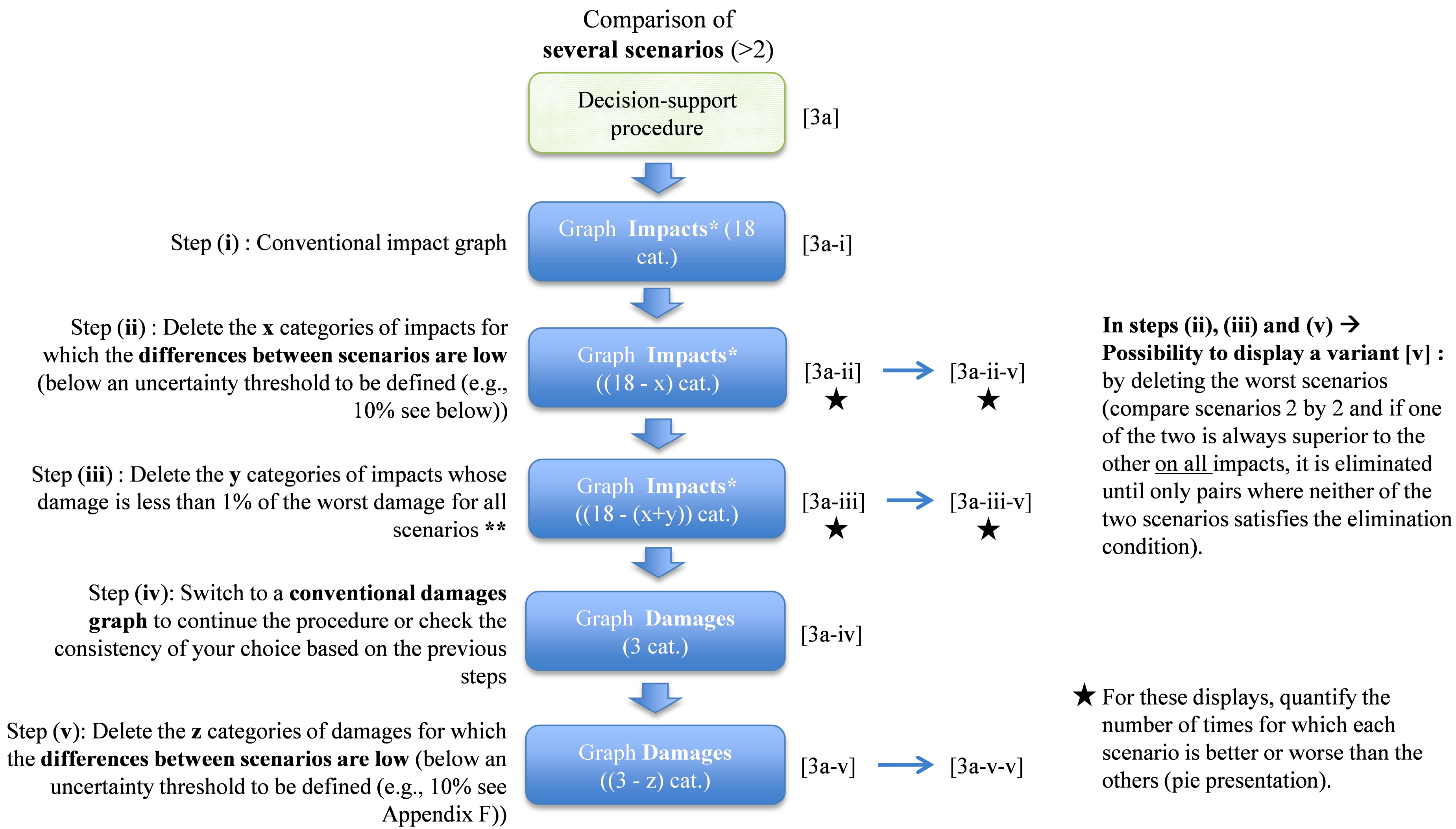
We developed a new method for presenting LCA results to elected officials and local authority technicians, applying the principles of simplification and graphs validated with the test-group. We introduced a complementary pie-chart representation which presents the number of times a scenario is the best and the number of times it is the worst.

The originality of this method consists in providing visual displays specific to each type of use (see 4.1) and in deploying with the user different steps which allow him or her to understand the simplifications made and to follow implicitly the ramifications of the decision tree. This method is therefore a synthesis of the procedure to simplify the graphs and the procedural approach of the decision tree. It is described in the following Figures (6 to 8) and was implemented in version 1.2 of ACV4E.



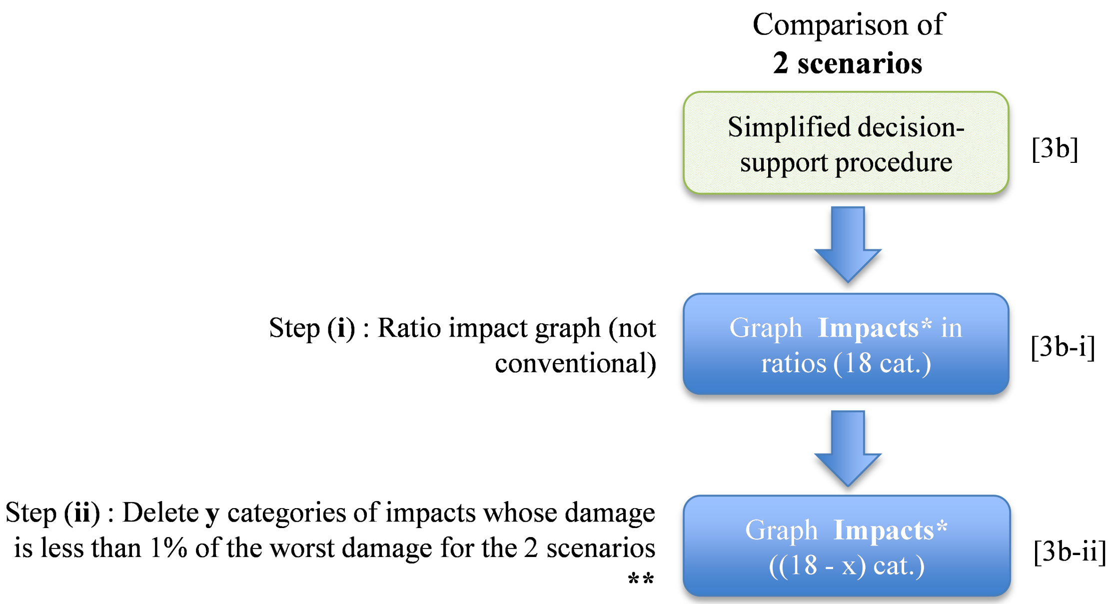
** Impacts regrouped in categories of damage (human health, resources, ecosystems)*

Figure 6 Proposition of three different modes of visualizing LCA results according to the user's objective (decision to be clarified)



** Impacts regrouped in categories of damage (human health, resources, ecosystems)*
*** The "Marine eutrophication" indicator, which is not quantified in damages, is always retained, in contrast, the "Water" indicator is always deleted.*

Figure 7 Decision-support procedure 3a for the display and analysis of ACV4E results for a choice by comparing several scenarios



** Impacts regrouped in categories of damage (human health, resources, ecosystems)*
*** The "Marine eutrophication" indicator, which is not quantified in damages, is always retained, in contrast, the "Water" indicator is always deleted.*

Figure 8 Decision-support procedure 3b for the display and analysis of ACV4E results for a choice by comparing two scenarios exactly

For the step in which non-discriminant criteria are removed, uncertainty thresholds between 10 and 30% were used, based on Jolliet et al. (2010, p.107). They are given in appendix F. Appendix F gives the correspondence between the graphs finally introduced in ACV4E and those tested.

5 Discussion: how to reinforce the relationship between scientific knowledge and public decision-making?

5.1 The solutions that enabled the appropriation of LCA by non-specialists

The experience of transferring the ACV4E software and the improvements made to it, particularly in terms of the display of results, made it possible to implement several solutions identified in point 2.4.3 (Table 3).

Table 3 Solutions implemented in the experiment to overcome difficulties in the use of LCA by non-specialists

Solution category	Detailed solution type	Implementation of the solution in ACV4E
Rationalist perspective		
Limit implementation costs	Develop less resource intensive methods	Principle of the simplified calculator (LCA conducted in 0.5 to 2 days, compared to many days otherwise)
Refine the assessment method (modeling impacts)	Undertake new research and consolidate existing methods to improve the relevance of environmental assessment	Improvement in the consideration of micropollutants (endocrine disruptors, nanoparticles, drugs, substances with very long persistence, etc.) Integration of a new impact on human health related to wastewater pathogens
Reduce the complexity of results	Simplified calculator (capitalize on expert knowledge)	Difficulty, however, in adequately developing systems to cover all types of diverse cases
	Format for the transfer of results and analyses adapted to a specific use	Possibility to export into Excel format Differentiated display depending on the use
	Systematize the heuristic supporting the interpretation	Establishment of a procedure for the progressive simplification of results
	Limit the number of criteria through selection	Application of user-independent, reproducible, rationally justified selection principles (e.g., discriminant criteria)
	Limit the number of criteria through aggregation	Use of endpoints (but never without having also analyzed the midpoints)
Relativist perspective		
Capacity building	Train users	0.5 to 1 day of training and/or tutorial integrated into the calculator
Intermediation	Call on intermediary actors	Both the role of researchers in relation to technicians and then of technicians (from local authority or consultants) in relation to elected officials
Institution design	Raise users' awareness of environmental issues	Sensitize users and hierarchy (prior to training)
Adaption to the need and decision-making context	Identify the target and the need to produce a method adapted to the demand	Different display of results depending on identified use
Transparency	Explain the underlying models	Parameterization of scenarios and analysis of results by the user Creation of a software tutorial integrated in the tool
	Open the black box	
Participation	Co-build the assessment method	Co-build ACV4E
Legitimization	Use recognized methods	Prior use of SimaPro software and the ReCiPe

		impact approach (widely used in LCA)

The experiment demonstrated that one important condition for enabling the appropriation of LCA in local authorities is to co-build the simplified calculator with the potential users. This reinforces the transparency and legitimacy of the LCA method.

5.2 From appropriating LCA to using it in decision-making

Will the environmental assessment made available to local authorities by ACV4E modify the investment decision? This question could only be partially addressed during the test, however some elements emerge.

LCA could potentially help reinforce the environmental dimension. In our field experiment, we sought to identify the usual criteria of decision-making and the part accorded to the environment when LCA is not used (Guérin-Schneider and Tsanga Tabi, 2017) (see Table I.1 in Appendix I).

While regulatory (choice of a technology ensuring compliance with discharge standards) and economic (choice of a less expensive technology) criteria dominate, the environmental dimension certainly is present. Apart from compliance with discharge standards, the usual criteria used for this dimension are rather poor and difficult to quantify. LCA thus potentially could provide much richer quantified information and thus give more weight to the environment.

Nevertheless, beyond the difficulty of interpreting highly multicriteria results, we identified three difficulties in the effective use of an LCA.

For local elected officials, geographically and temporally close impacts are very important. Accepting the use of LCA means recognizing that the impacts close to us in space and time are equally important as those that occur far away and much later.Yet tension has sometimes been noted during the field test and the decision-maker does not necessarily accept the equally importance of impacts suggested by LCA.

A second point emerges: the difficulty of attributing an absolute severity level to impacts, which would make it easier to rank them. In this context, the use of LCA for strategic ends, to highlight those criteria which support a decision already made based on other criteria (cf. Figure 4 strategic behavior), could not be totally avoided. In this regard, research on the notion of planetary boundaries, at present still in its early stages, will undoubtedly open up new perspectives (Rockström et al., 2009a; Rockström et al., 2009b). The task is to attribute more objectively a character of severity to different types of impacts according to the degree irreversibility in planetary equilibriums.

The third point is the importance of dominant formal rules. European urban waste water directive focuses on the quality of the discharge level. This leads decision-makers to place the treatment system's ability to provide the level of treatment required above all other environmental criteria (see Table I.1 in Appendix I). This situation contradicts LCA philosophy, which does not *a priori* give priority to any one type of impact. This questions the role of regulations in the dissemination of innovations such as LCA.

Our experiment emphasizes the role of potential translator-actors of the innovative tool and the efforts needed to simplify and co-build this tool in order to adapt outputs to the decision-making context. It may also be necessary to change the regulatory context to become more compatible with LCA philosophy.

6 Conclusion: the contribution of management sciences to LCA

As already highlighted by Riot (2014), for a broad dissemination of LCA among non-specialists, the analysis of decision-making and the development of methods to present results should receive full attention. Management sciences thus should be considered as a discipline to mobilize for future developments in the LCA field.

Our analysis based on management science aimed to identify the barriers behind the still weak dissemination of LCA to support public decision-making. This raised the question of the conditions for the mobilization of scientific knowledge in decision-making by non-scientists. After identifying the various types of obstacles to this appropriation through a literature review, we identified possible solutions to overcome them.

We then applied some solutions in the operational context of local authorities seeking to choose between several investment scenarios for a wastewater treatment system. We tested and co-built with local authorities a simplified LCA calculator. From a positivist perspective, this approach made it possible to limit the cost of implementing an LCA, refine impact modeling to meet the needs of the wastewater sector, and reduce the complexity of the results. From a relativist perspective, it fostered capacity-building and intermediation, changed how the value of the environment is integrated into decision-making, improved the adaptation of the LCA tool to needs, and provided more transparency, participation and legitimization.

This research has opened the way to facilitate the use of LCA by non-specialists: local decision-makers, technicians and elected officials. Special attention should be paid to the display and interpretation of results. Several principles emerge to facilitate interpretation. The production of the standard endpoint and midpoint graphs used by LCA experts is not enough. The information given in results must be reduced to what is really useful for the decision. We propose a transparent decision-support procedure which enables to reduce the number of midpoints, keeping only the most discriminant and impacting ones. We also suggest graphic representations to determine the number of times a scenario is considered better than others. These principles can be generalized to other contexts where LCA may be used by non-specialists.

This is only a first step toward understanding decision processes involving LCA in the public sector. Next question will be: once information arising from LCA is made easier to understand by non-specialists, what is the effect on decisions. This encourages the further pursuit of joint research between LCA and management science researchers. Such work will not only facilitate the dissemination of LCA in the context of decision-making, but also renew certain research questions on the impact of LCA on decision-making and, more fundamentally, on the relationship between value systems and implementation of LCA.

7 Acknowledgements and funding sources

The research was supported by by Irstea (member of the Carnot Institute), AFB (French Agency for Biodiversity), the Rhine Meuse and Rhone Mediterranean Water Agencies, and the Departmental Councils of Bas-Rhin and Hérault.

The authors thank Evelyne Couliou, Jean-Luc Lablée and Eva Risch, researchers at Irstea, and local authorities for their involvement throughout the field experiment. We thank the Agence Régionale pour l'Environnement et l'Ecodéveloppement PACA, which supported the initiative.

The authors thank the two anonymous reviewers who helped to improve this article.

Finally, the authors thank Grace Delobel for her translation work that was funded by the Industrial Chair for Environmental and Social Sustainability Assessment "ELSA-PACT" (partners of the Chair: ANR, the Occitanie Region, AFB BRL, SCP, SUEZ Groupe, VINADEIS, Compagnie Fruitière).

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Supplementary Material

Appendix A: Presentation of Life Cycle Assessment principles

The LCA method consists first of establishing an inventory of all pollutant emissions in the environment and of all the natural resources consumed during the life cycle of the system studied. Environmental impacts are then calculated at three levels: global impacts (greenhouse effect, depletion of the ozone layer...), regional impacts (eutrophication…), and local impacts (human toxicity, ecotoxicity...). The list of impacts taken into account by LCA has been enriched with advances in scientific knowledge on impact mechanisms. This list constitutes what LCA experts call “midpoint” indicators.

The next step, one much less consensual from a scientific perspective, is to estimate the consequences of these impacts on three protection areas: human health (measured in days of life lost), ecosystems (quantified as indicators of biodiversity loss) and consumption of natural resources (quantified as energy or monetary value). These are referred to as “endpoint” indicators. This stage of damage assessment is less scientifically consensual because it has a greater margin of uncertainty.

In LCA, impacts are referred to as potential. Impacts are reduced to the unit of service delivered (for example, the impacts associated with the production of one kg of product over its entire life cycle). LCA thus does not quantify actual pollution, which must take into account all of the pollutant fluxes generated by the activity concerned (the entire plant) and combine this with the pollution resulting from all of the other human activities on the ecosystem concerned. This is why LCA is an exclusively comparative method that renders it possible to (i) compare the eco-efficiency of different systems providing the same service, and/or (ii) analyze the relative contributions of the components of a single system.

Appendix B: Presentation of the operational partners involved in the field test

Table B. 1 Principal characteristics of the ACV4E tool test sites (local authorities)

Local authority[2]	**Type of local authority (management mode*)**	**Degree to which sustainable development is considered in the organization's operations**
Montpellier Méditerranée Métropole (MMM) 430 000 inhabitants	Inter-municipal structures (delegated)	Commission of elected officials on the topic: Agenda 21, climate plan
Partnership involving the Rhin-Meuse Water Agency, the Alsace Moselle Water and Sanitation Syndicate (SDEA) and the Bas-Rhin Departmental Council 800 000 inhabitants	Inter-municipal structure (delegated and direct management)	Partnership agreement on sustainable development training between the 3 local actors SDEA certified as a sustainable development and environment organization Effort to reduce carbon impact of structures
Vienn' Agglo 67 800 inhabitants	Inter-municipal structures (delegated and direct management)	Environment department (in charge of climate plan) separate from the department overseeing water networks
Chateaurenard 37 000 inhabitants	Municipality (direct management)	Agenda 21 program with an elected official as leader and a sustainable development orientation
Sarrians 5 800 inhabitants	Municipality (direct management)	No department dedicated to sustainable development
Puget-ville 3 800 inhabitants	Municipality (direct management)	Proactive policy on the part of elected officials with the adoption of a sustainable development charter and a task officer

* Direct management: service operated by a public entity under the direction of the local authority. Delegated: service operations delegated to a private company.

Also involved in the test were the following:
- the Hérault and Bas-Rhin Departmental Councils, which are local authorities operating at a higher level than municipalities. They are charged with providing support, particularly to rural communes, in setting up sewerage systems. A Departmental Council notably intervenes to draw up master plans that determine the major technical choices for a 10-year sewerage service.
- two consulting firms (Entech and V2R) specializing in project management of wastewater systems whose role is to propose and dimension various technical solutions in order to define an investment project.

[2] The predominance of local authorities in the Rhône Méditerranée Corse Basin is due to the fact that the project received funding from this Water Agency to form a pilot group.

Appendix C: Conduct of the test on the display of results and interpretation procedure

The test group gathered 15 people:
- technicians from local authorities and external consultants providing support to local authorities for wastewater projects, all trained in how to handle and use the ACV4E software,
- people involved in the project but who had not handled the tool (Rhône Méditerranée Corse Water Agency (AERMC) and the Regional Agency for the Environment of the Provence Alpes Côte d'Azur region(ARPE)),
- an elected official (from a local authority supported by the Departmental Council of Hérault (CD34)), who had not handled the software,
- a student, representing an average user, who had not used the software,
- researchers who developed the software,
- researchers in management sciences involved in the project.

The objective was not to constitute a representative sample of a population of users, but to have a sufficiently diverse and numerous group to test the qualities and limits of the different representations. The aim therefore was to conduct a qualitative analysis to improve the way results are displayed. The precise composition of the test group with the attributes of the individuals involved is provided in Table C. 1. The individuals had varying levels of knowledge about sanitation and LCA (expert to novice).

The detailed composition of the test group is detailed in Table C. 1.

Table C. 1 Composition of the test group

Individual code	Organization	Type of organization	LCA proficiency	Wastewater proficiency	ACV4E knowledge	Training	Position
T1	Puget-Ville	Small local authority	average	high	Average	technical	local authority technician
T2	M3M	Large local authority	average	high	Average	technical	local authority technician
T3	CD34	Other public actor	average	high	Average	technical	consultant (and elected official)
T4	CIRAD	Research institute	high	low	low	technical	LCA researcher
T5	Irstea	Research institute	low	low	low	management	user
T6	Irstea	Research institute	high	average	high	technical	LCA researcher
T7	Irstea	Research institute	average	average	average	mixed	Management researcher (and former consultant)
T8	SDEA	Large local authority	average	average	average	technical	local authority technician
T9	AERMC	Other public actor	average	high	average	technical	consultant
T10	ARPE	Other public actor	average	high	average	technical	consultant
T11	Entech (consultant of M3M)	Consulting firm	average	high	average	technical	consultant

Individual code	Organization	Type of organization	LCA proficiency	Wastewater proficiency	ACV4E knowledge	Training	Position
T12	SI CAMMAOU*	Medium-size local authority	low	low	low	technical	elected official
T13	Irstea	Research institute	high	average	high	technical	LCA researcher
T14	Irstea	Research institute	average	low	low	management	management researcher
T15	Chateaurenard	Medium-size local authority	average	high	average	technical	local authority technician

* intercommunal syndicate assisted by CD34

The test was conducted over one day. It took place in French (graphs in French), the mother tongue of the participants and the language used in the ACV4E software. Participants were placed in a situation of having to choose between several sanitation investment options. This was thus the use initially planned for the ACV4E software (see 4.1). After briefly explaining the principle of the presentation of each graph, different graphs presenting LCA results for the comparison of three (or sometimes two) scenarios were successively presented. The same three scenarios were always presented.

To be as close as possible to what would be a real decision-making situation, we used in the graphs actual LCA results comparing three treatment systems. They are detailed in Appendix H. However, we intended to capture only the influence of the graphical format and the formal simplification procedure. It is recognized in psychological sciences that contextual factors associated with options can influence choice (Corneille, 2010). This is why, although the results were based on actual LCAs, the investment options (scenarios) were presented generically ("scenario 1, 2 and 3") without specifying their nature or the context of the decision. We gave no information about the nature of the scenarios, the functional unit, etc.. This protocol was adopted so that technical considerations related to the subjective perception of the nature of the scenarios would not influence responses.

The scenarios were deliberately chosen to be difficult to choose between. In the standard presentation of results (18 midpoints), two scenarios are either the best or the worst on an equivalent number of midpoint criteria.[3] The third is an intermediate scenario, most often located between the two others (see Figure C. 1, graph H1).

[3] The LCA method used for the assessment of impacts and damage is ReCiPe (the method used in ACV4E).

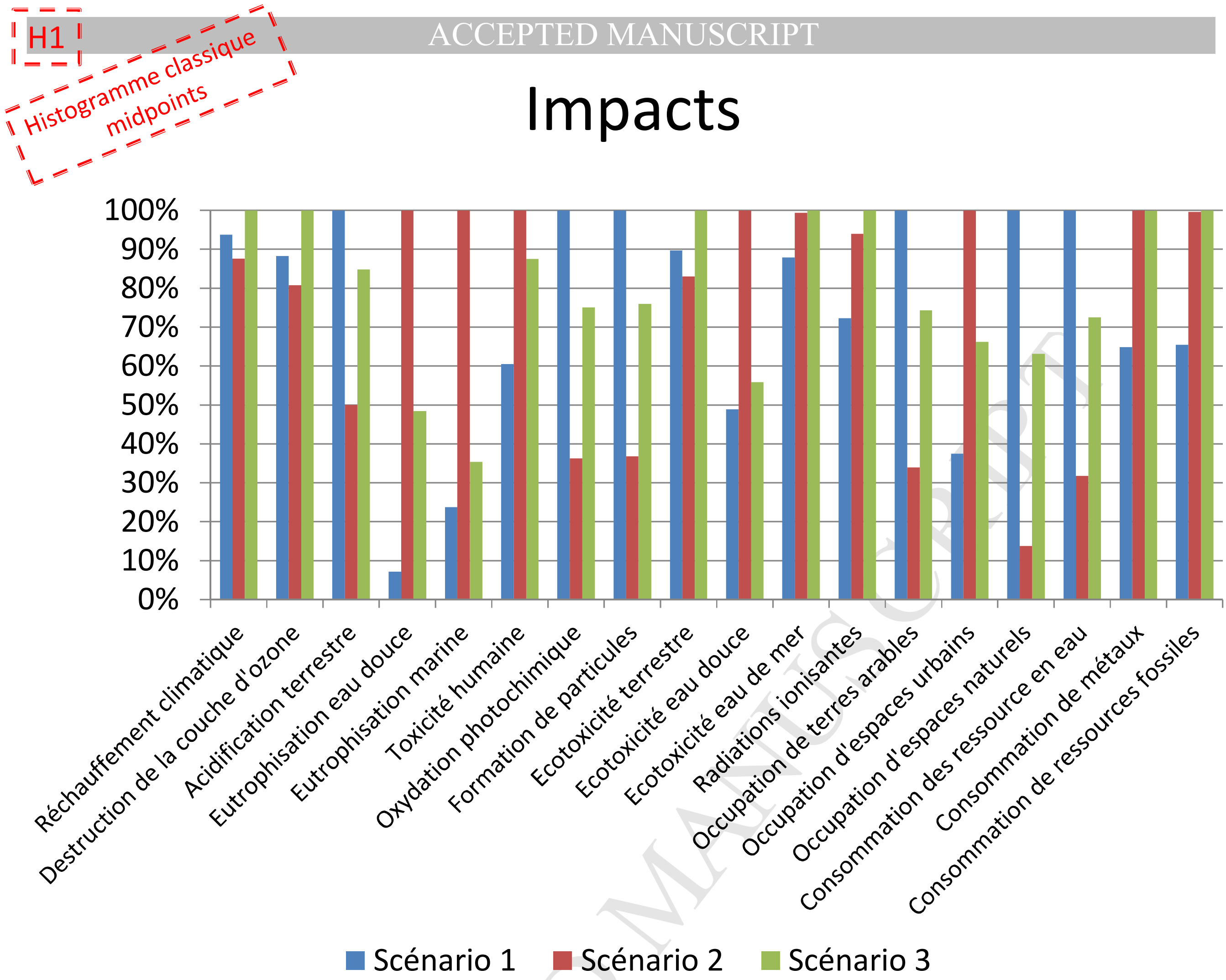


Figure C. 1 Graph H1: conventional midpoint histogram

A total of 10 visual displays were tested, as was a decision tree proposing a procedure based on successive questions to guide the interpretation of the results.

The list of graphs and the decision tree are presented in Table C. 2. Some graphs (indicated with a ‘V’) are variants of the main graphs.

Table C. 2 List of the representations tested

Code	Full name	Short name
H1	Conventional midpoint histogram	Conventional midpoint histo
H2	Conventional endpoint histogram	Conventional endpoint histo
H3	Ranked midpoint histogram	Ranked midpoint histo
H3V	Ranked and highlighted midpoint histogram	Ranked highlighted midpoint histo
H4	Midpoint subset histogram (severity)	“Severity” midpoint subset histo
H4V	Ranked and highlighted midpoint subset histogram (severity)	Ranked highlighted "severity" midpoint subset histo
H5	Ranked and highlighted midpoint subset histogram (severity and discriminant)	Ranked highlighted severity and discriminant midpoint subset histo
H6	Endpoint histogram with contribution of midpoints	Histo endpoints + contribution midpoints
H6V	Endpoint histogram with contribution of midpoints broken down	Histo endpoints + contribution midpoints broken down
H7	Conventional midpoint histogram (2 scenarios exactly)	Conventional midpoint histo (2 sc.)
H8	Conventional endpoint histogram (2 scenarios exactly)	Conventional endpoint histo (2 sc.)
H9	Midpoint histogram on a balance	“Balance" midpoint histo
H10	Midpoint histogram showing ratio between scenarios	"Ratio" midpoint histo
DT	Decision tree (for investment choice)	Tree

Appendix D presents the different graphs used in the test.

After the presentation of each new graph, respondents filled out a questionnaire to find out:
- the procedure or the reasoning applied to determine a choice based on the graph presented,
- the decision taken ("what is the best scenario from an environmental point of view?"),
- whether it is easy or not to make a choice based on the graph,
- whether the principles of representation are easy to understand,
- whether or not the graph is easy to read,
- their opinion on the qualities of the graph *vis à vis* the profiles of different potential recipients (elected officials, users, water police) taking into account the fact that most of the testers had a local authority "technician/adviser" profile (only one elected official present).

At the end of the session, respondents were asked to rank the graphs and give their opinion regarding which principles of presentation and/or simplification of the results should be retained.

The following bullets points details every question that was submitted to the test group. They summarized the results obtained. The new interpretation-support procedure proposed in the article was based on these results.

- **Choice of the best scenario based on different graphs**

The first finding was clear: although the scenarios presented were the same each time, the choice of the best scenario varied depending on the graph presented. The rate of uncertainty also decreased as principles of simplification/explanation were applied. Finally, as may be expected, the rate of uncertainty was lower for endpoint representations (3 indicators only) than for classic midpoint representations (18 indicators). A distinction was made between the response "don't know" (the respondent explicitly declared that he or she was unable to determine which scenario was best by ticking a box) and a lack of response (the respondent checked nothing).

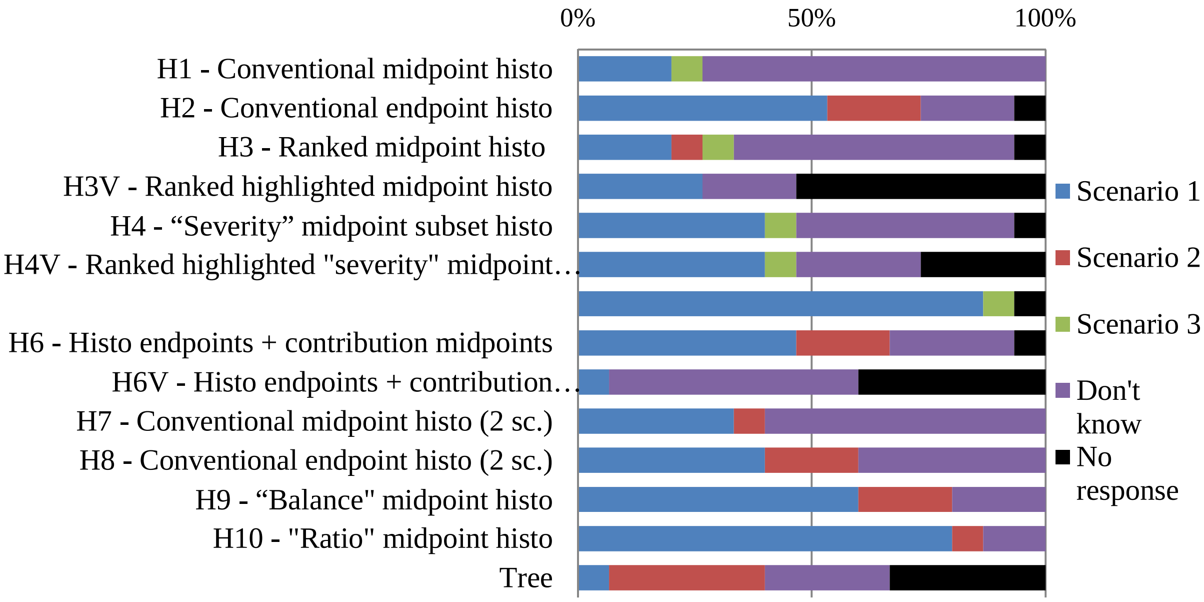


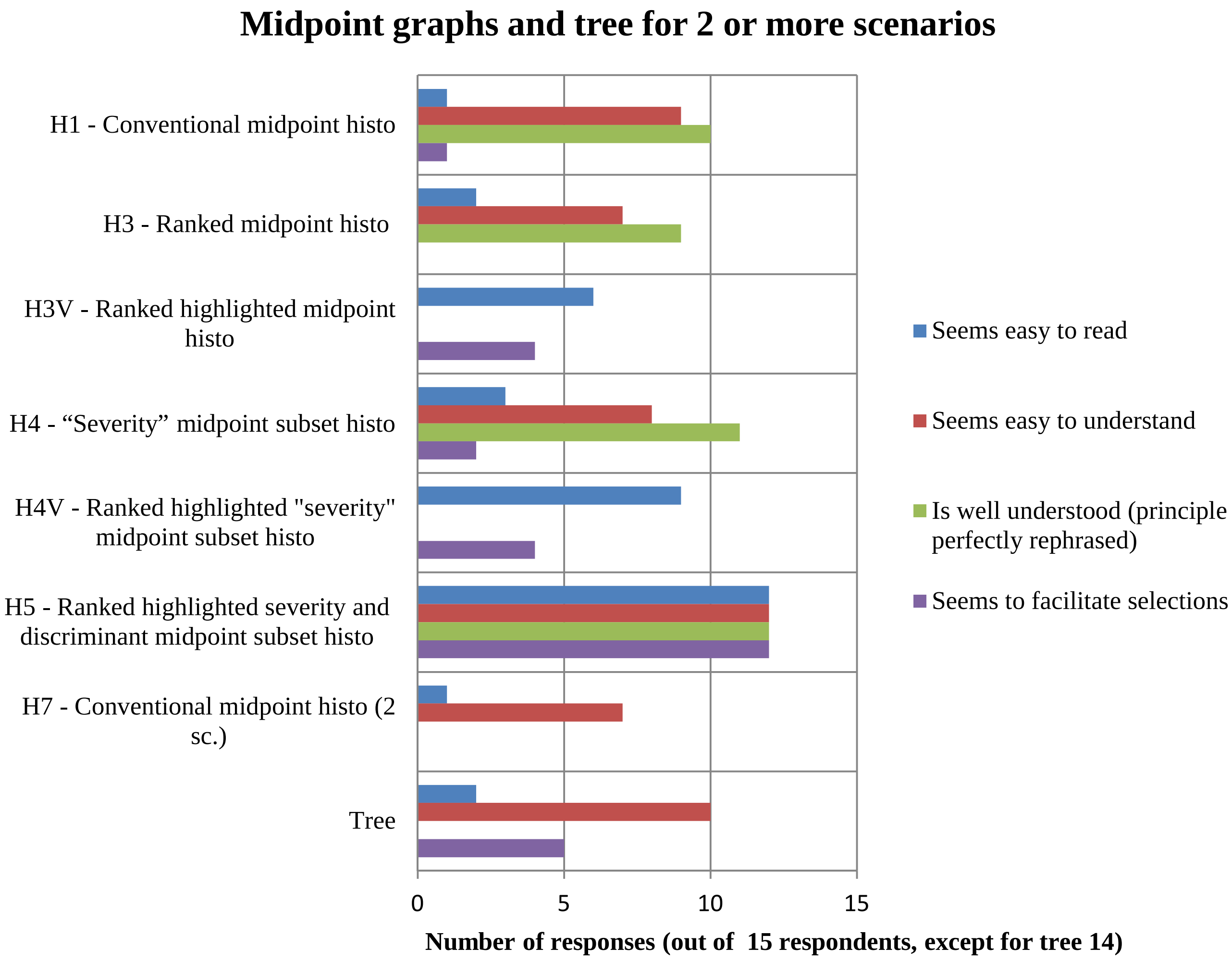
Figure C. 2 For each tested graph, answer to the question "What is the best scenario from an environmental perspective?"

- **Qualities of the graphs as seen by the respondents**

For each graph, the respondents were asked to indicate on a scale of 1 to 5 if the graph:
- was easy to read
- was easy to understand (subjective response)
- easily facilitated the selection of a scenario (the principle of representation may be easy to understand yet the choice of the scenarios can be difficult to do).

In an open question, respondents also were asked to rephrase the principle of presentation of the graph (this question renders it possible to see more objectively whether a graph is indeed easy to understand or not).

Figures C.4 and C.5 summarize the responses to these questions for the midpoint and endpoint representations, respectively. The results show that respondents found the most strengths in the following graphs:
- by midpoint for more than 2 scenarios: H5 – severity and discriminant midpoint subset histogram
- by midpoint for 2 scenarios exactly: H10 – midpoint histogram showing ratio between scenarios
- by midpoint for more than 2 scenarios: H2 – convention endpoint histogram or H6 – Endpoint histogram with contribution of midpoints



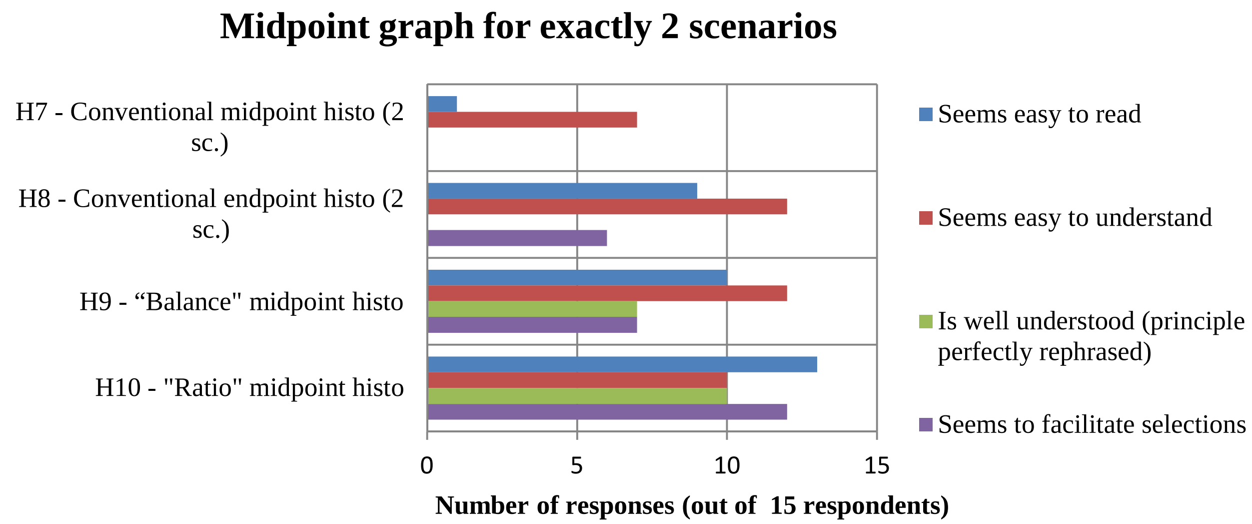


Figure C. 3 Quality of the graphs as seen by the respondents (midpoints)

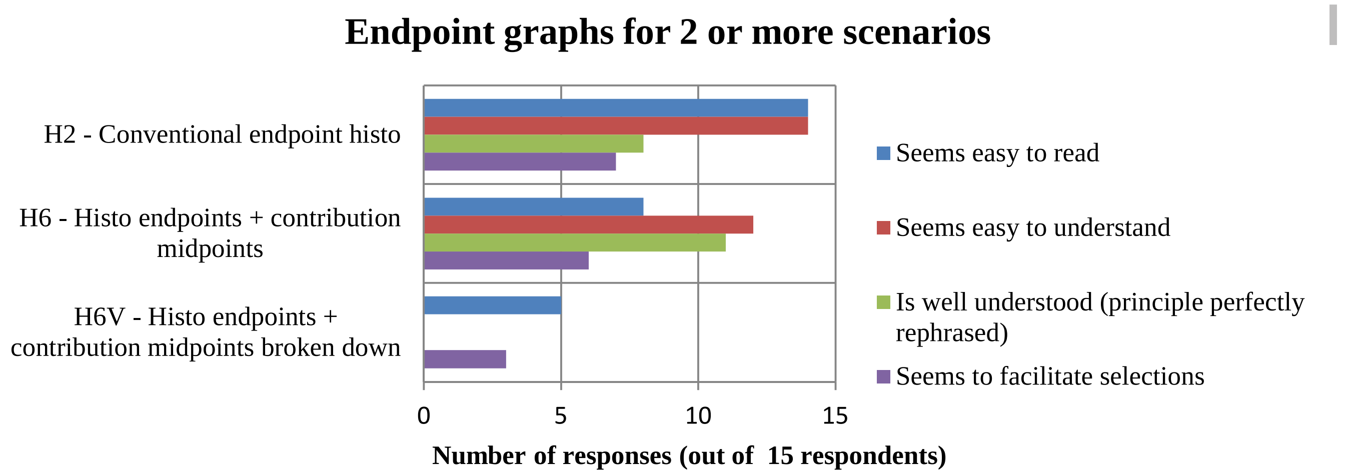


Figure C. 4 Quality of the graphs as seen by the respondents (endpoints)

- **Preferred display mode**

To go further, respondents were asked to rank in order of preference the three graphs they thought would be most relevant for presenting the results of an LCA to:
- elected officials of a local authority,
- technicians of a local authority.

For the midpoints, respondents had to rank three graphs (with the possibility of making just one or two choices only if they deemed the remaining graphs inappropriate to present to elected officials or technicians).

Figure C. 5 shows that the respondents made a distinction according to the category of user that was to view the results. For elected officials, who were deemed less able to understand a complex representation from a technical point of view, one representation clearly emerges, often in an exclusive manner: H5 - severity and discriminant midpoint subset histogram.

For technicians, the representation that is most often preferred is even more clearly H5. But in their case, other representations are deemed admissible, notably H4V – Ranked highlighted “severity” midpoint subset histogram.

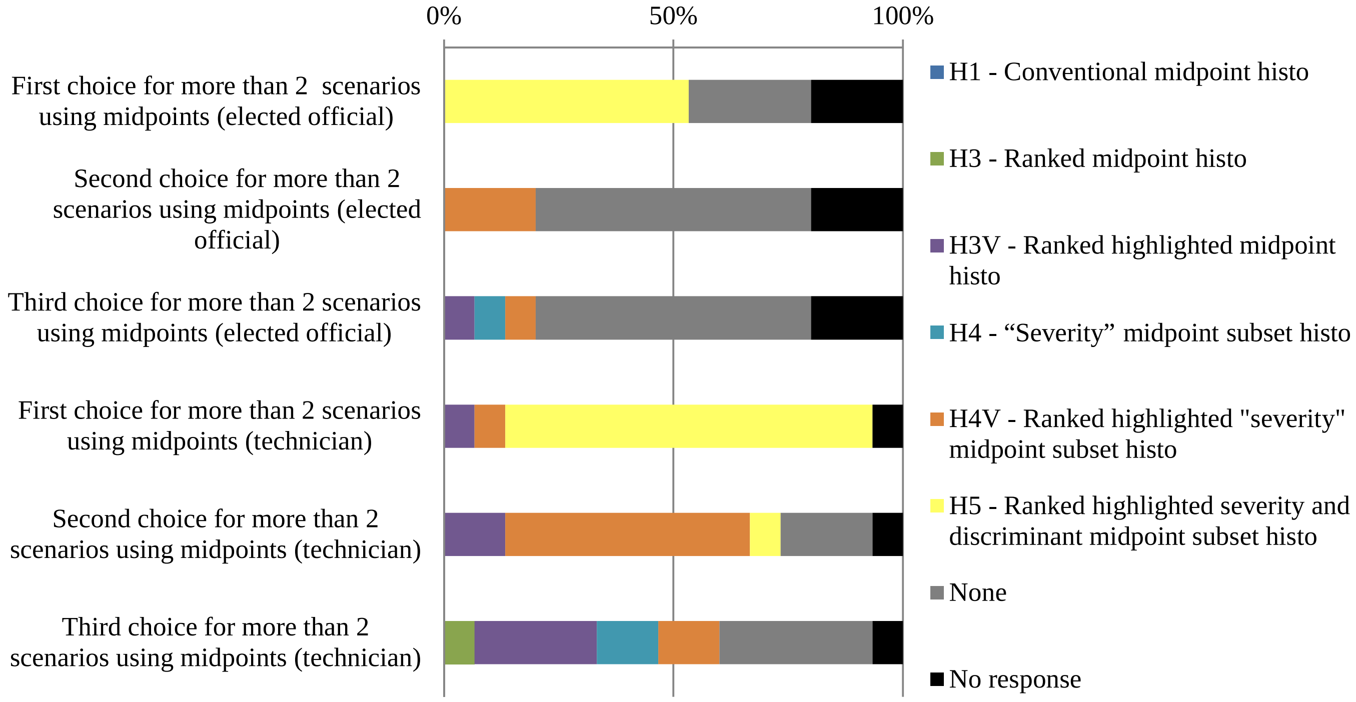


Figure C. 5 Which displays are preferred for use with an elected official or a technician (three choices ranked for each)?

For the endpoint graphs and midpoint graphs for exactly 2 scenarios, the number of representations being limited, only one choice was possible, either for use by elected officials or for use by technicians.

This time, the displays preferred for elected officials are less clear. For the endpoint graphs, the conventional display (H2) is slightly preferred over H6, which presents the midpoints' contributions to the endpoints. The display which is the simplest and the most aggregated was judged to be better adapted for choices by elected officials. For the midpoint graphs for 2 scenarios exactly, H10 is slightly preferred over H9.

For technicians, H6 and H10 were preferred.

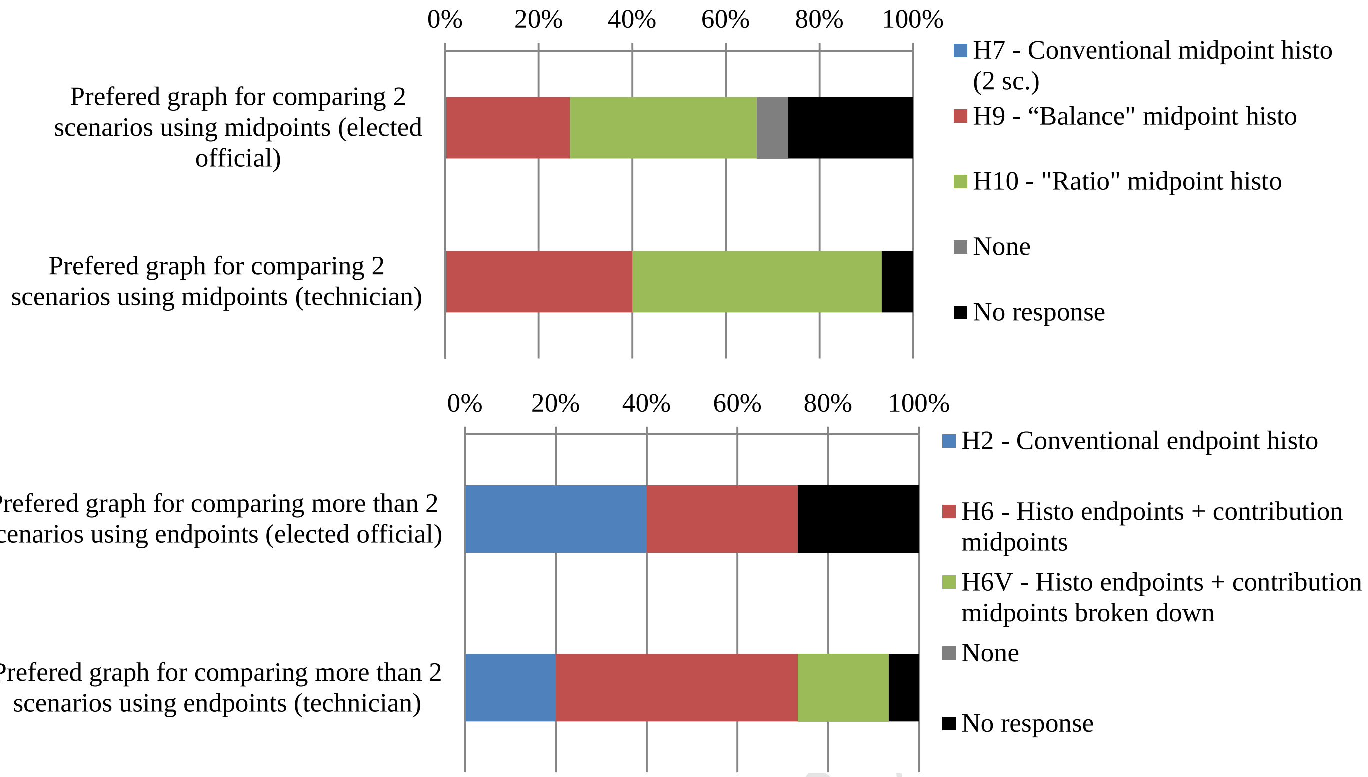


Figure C. 6 Preferred graph for presenting the results to elected officials and technicians (respectively endpoint graphs and midpoint graphs 2 scenarios exactly)

- **Respondents' recommendation on the simplification/explanation principles to be retained**

To complete the test, respondents were asked to explicitly indicate which principle of simplification/explanation was relevant to them or not.

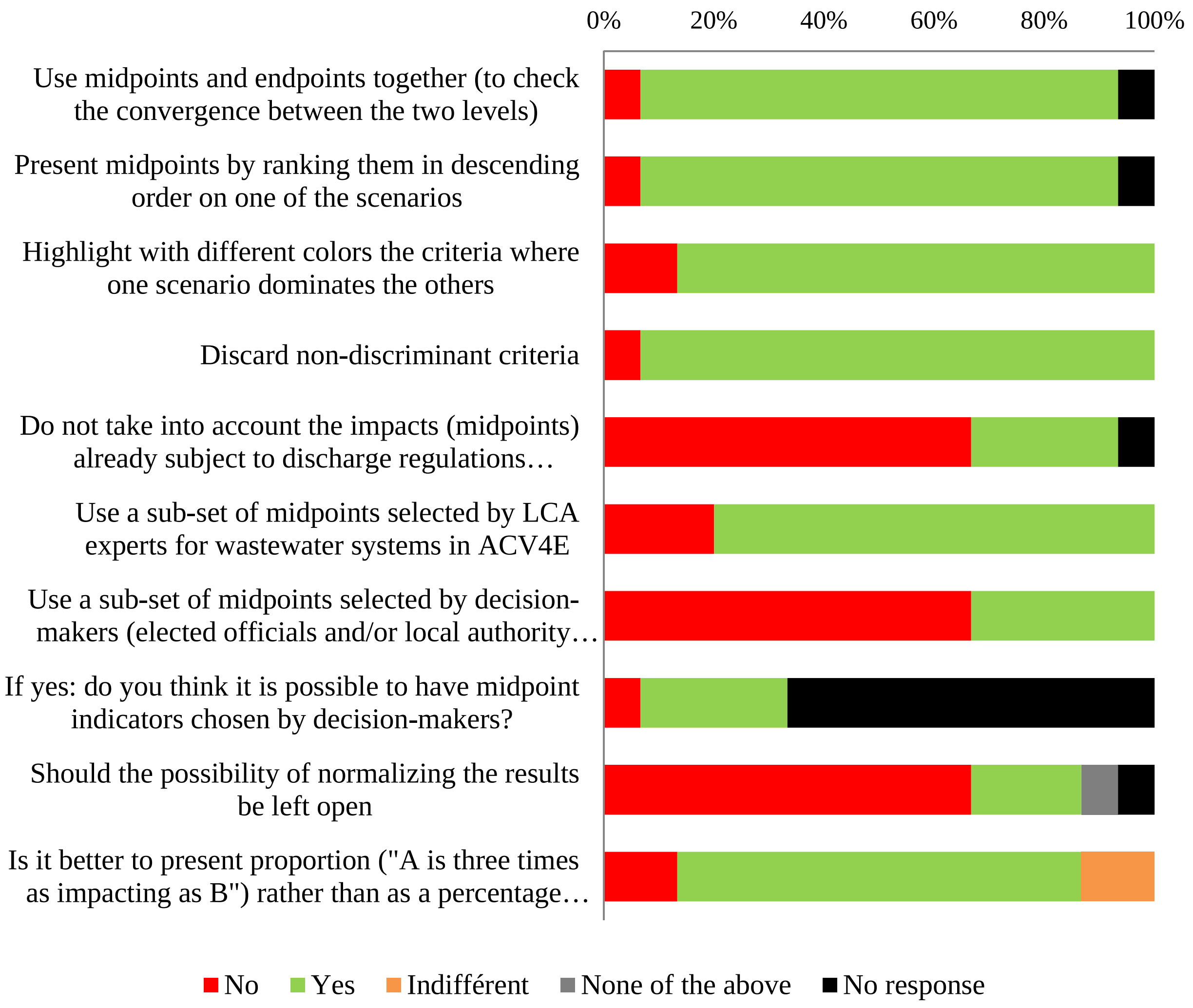


Figure C. 7 Respondents' opinions on the simplification principles to retain

Note: "Do not take into account impacts already subject to discharge regulation" (5th simplification) refers to the fact that a treatment plant has to respect regulatory obligations. This simplification proposes that if an impact category already is regulated by law, and assuming that this regulation is respected, it is not useful to consider the above mentioned impact because the regulation is supposed to guaranty the preservation of the environment on the regulated criterion.

Almost all of the principles of simplification were validated, with the exception of removing the criteria subject to regulatory requirements and of using a subset of midpoints selected by decision-makers. The latter result supports the opinion of the LCA developers who wished to avoid this principle of simplification (see 2.4.3).

In the end, the group recommended to:
- retain both a presentation of midpoints and endpoints,
- use a midpoints presentation that only shows the most impacting in terms of damages,

- rank impacts in descending order for one of the scenarios (with the disadvantage of creating an asymmetry of treatment between the scenarios),
- visualize through highlighting which scenario dominates the others (with the disadvantage of focusing more on the number of times a scenario is the best rather than on the number of times that it is the least good),

- use “impacts/damages” terminology,
- not eliminate the impacts subject to regulatory requirements (eutrophication),
- eliminate normalization (source of confusion).

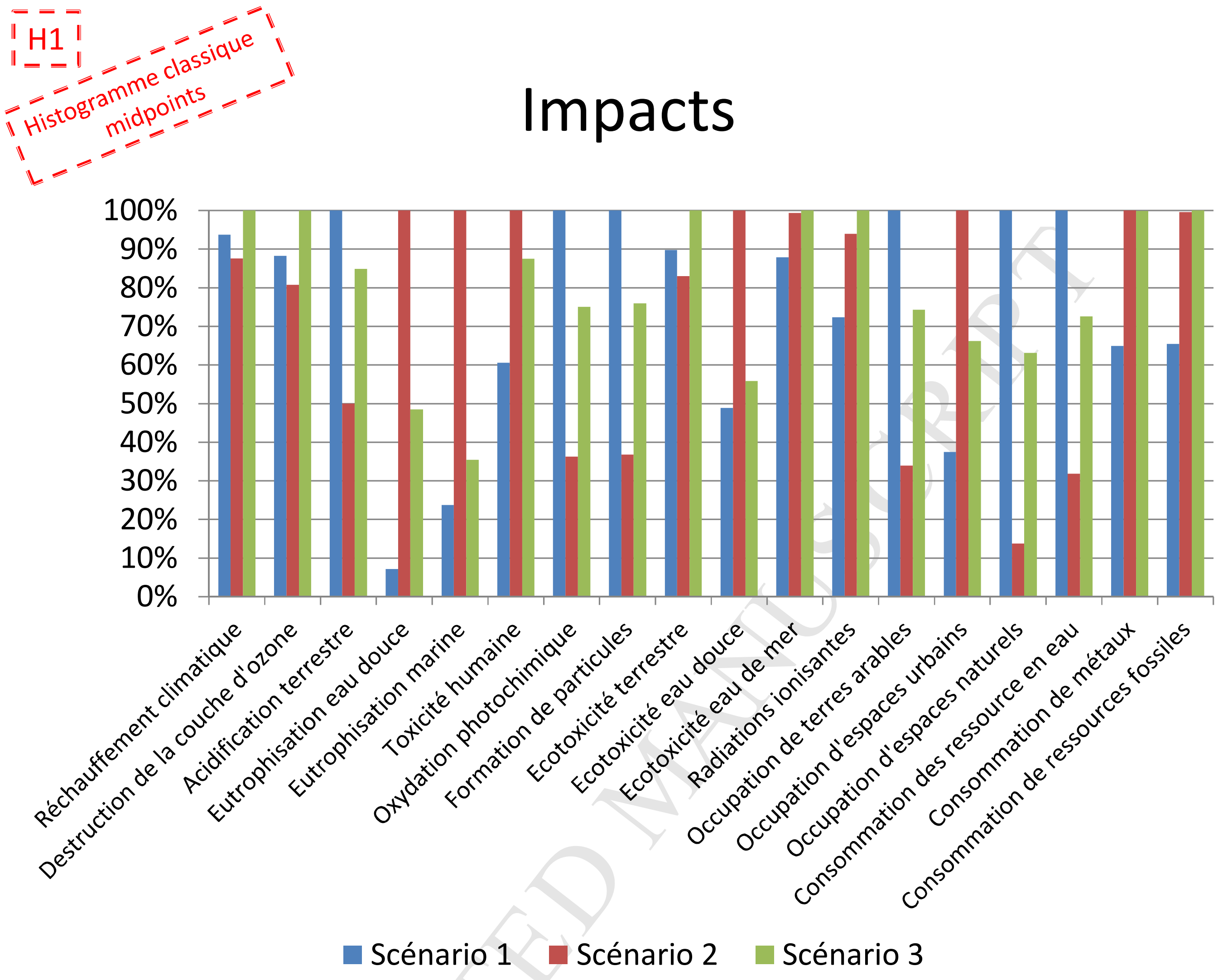
In their comments, the respondents suggested:
- less technical headings for the criteria: it is not easy for non-LCA specialists to understand the content of the impacts, or even to imagine what exactly is quantified by the damage criteria,
- some suggested to rank midpoints by main families, which implicitly constitutes an intermediate aggregation.

- **Use of the decision tree**

The comments received during the test session about the decision tree confirm the value of having a module in the software that guides the choice step by step. This module will gradually carry out the simplifications by applying the principles validated above. This collective work led to the proposals for improvement presented in section 4.3.3.

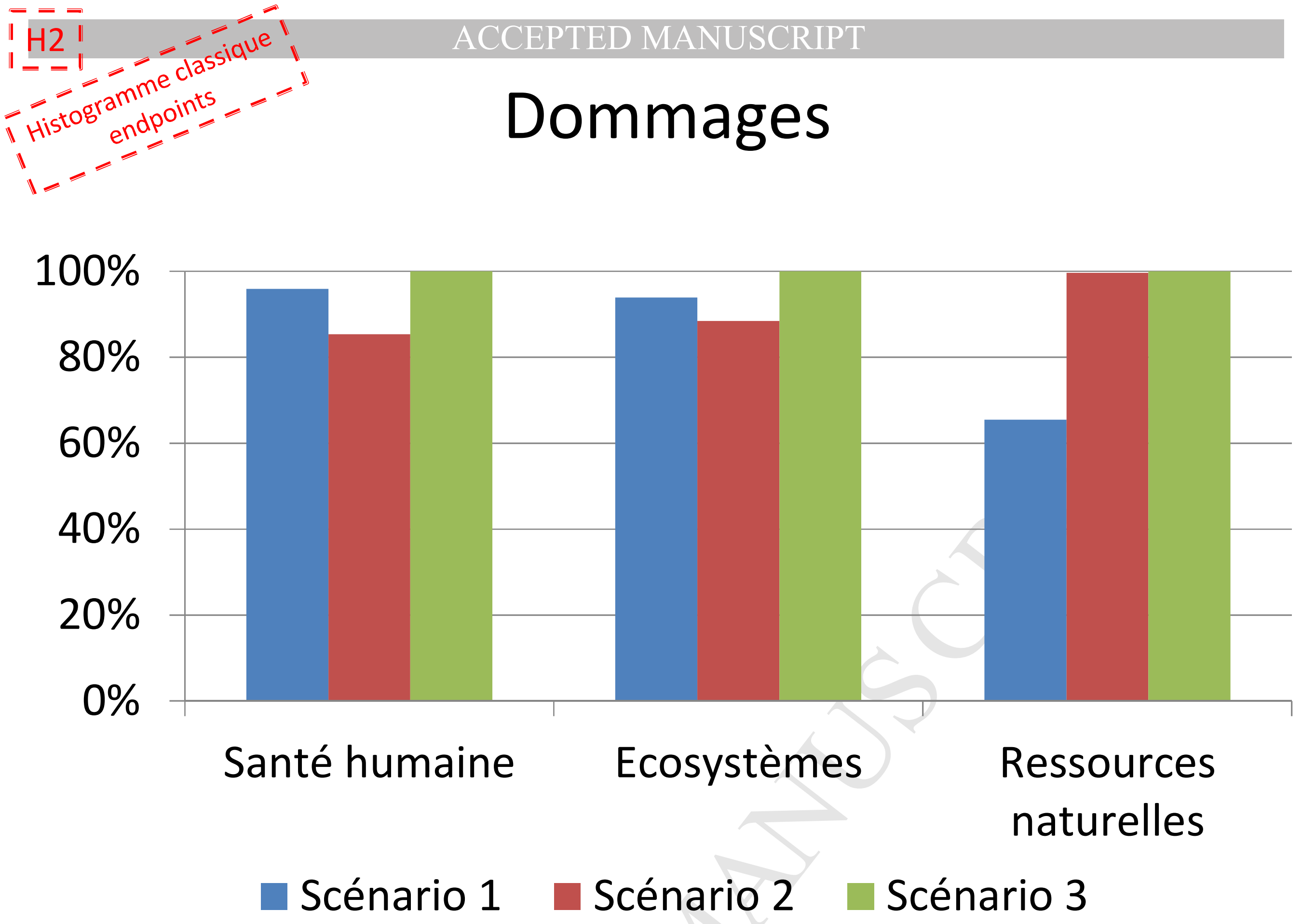
Appendix D: Graphs tested

The following graphs are reproductions of the graphs presented during the test. They are for this reason in French.



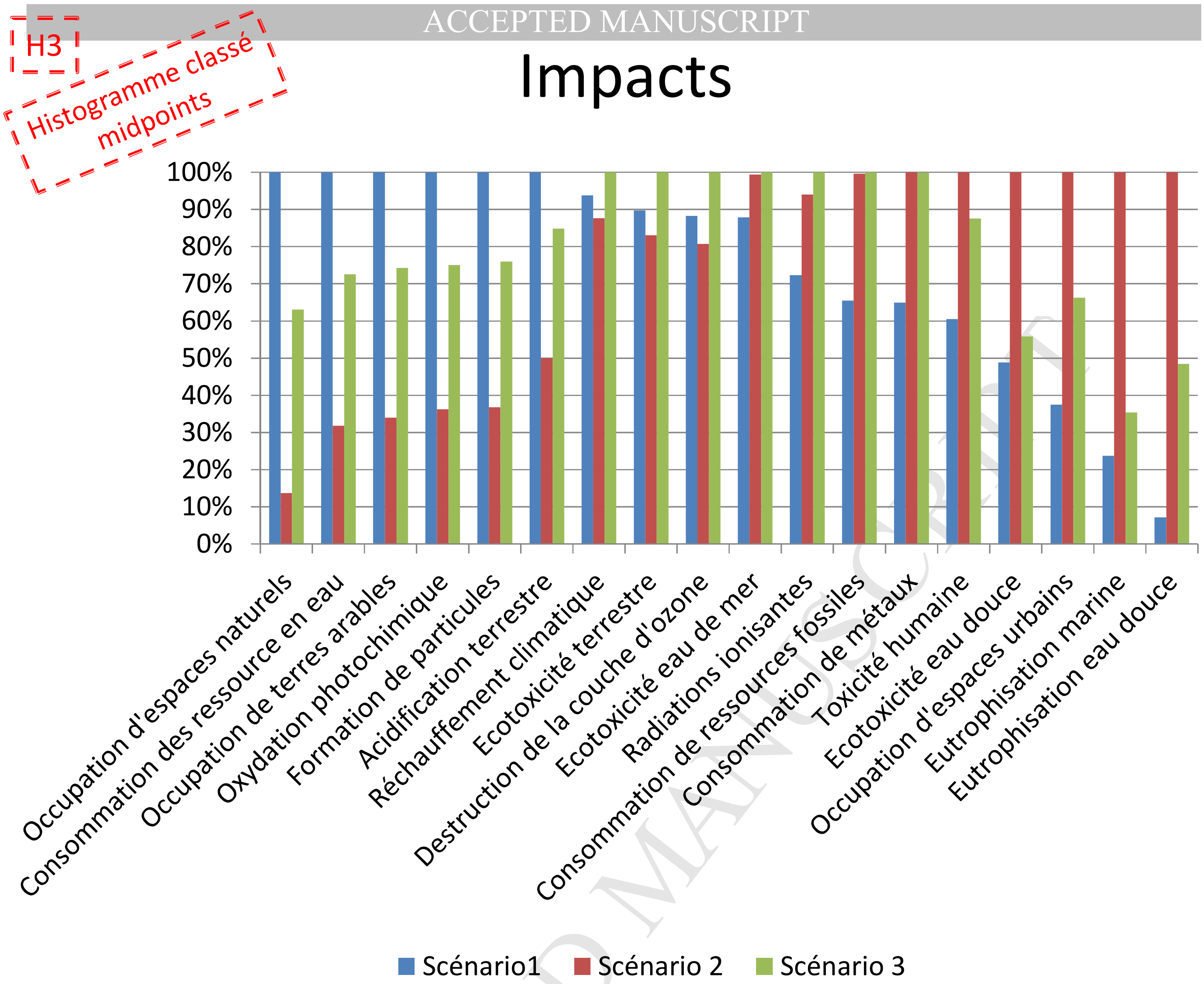
©Irstea

Figure D. 1 H1 Conventional midpoint histogram



©Irstea

Figure D. 2 H2 Conventional endpoint histogram



©Irstea

Figure D. 3 H3 Ranked midpoint histogram

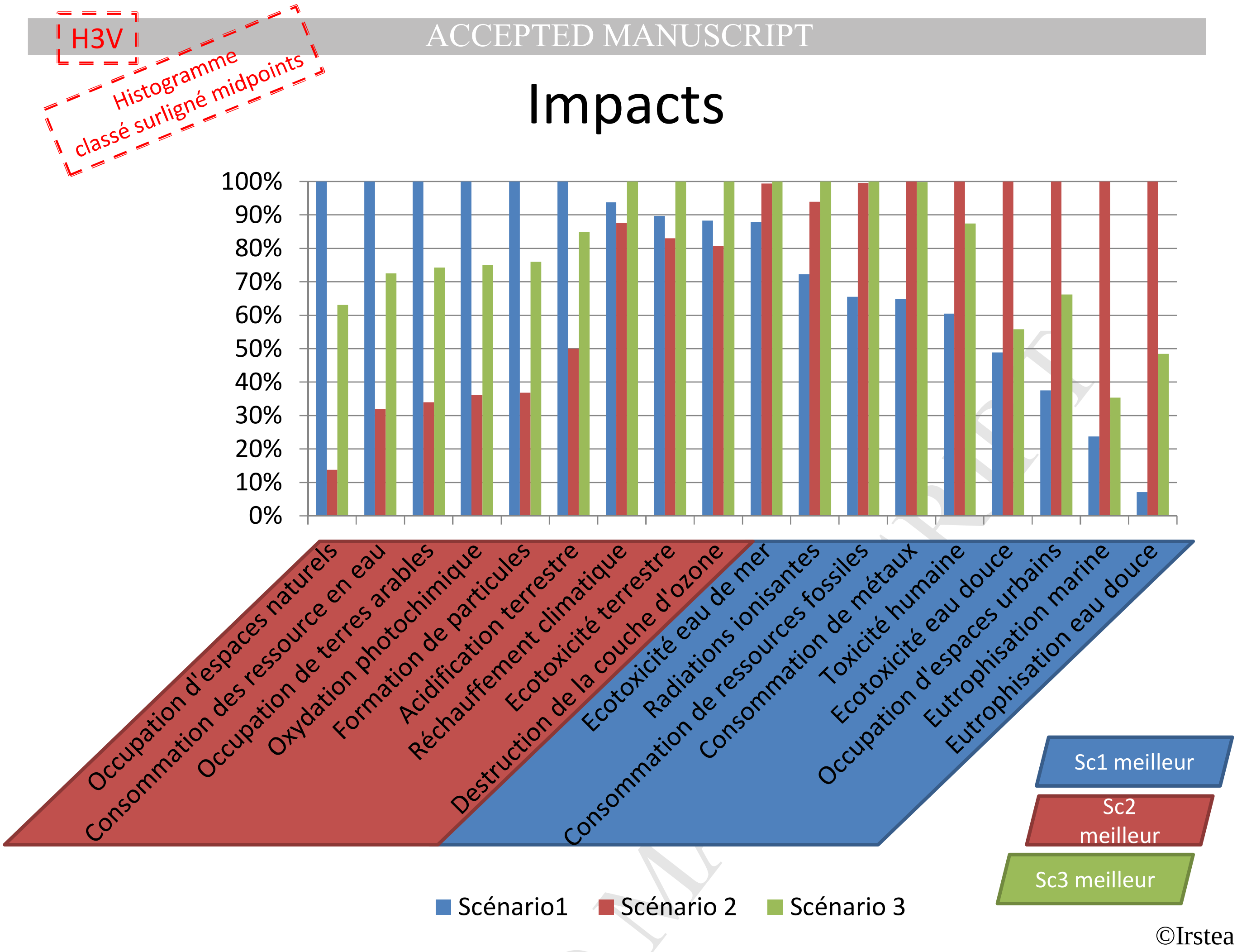


Figure D. 4 H3V Ranked and highlighted midpoint histogram

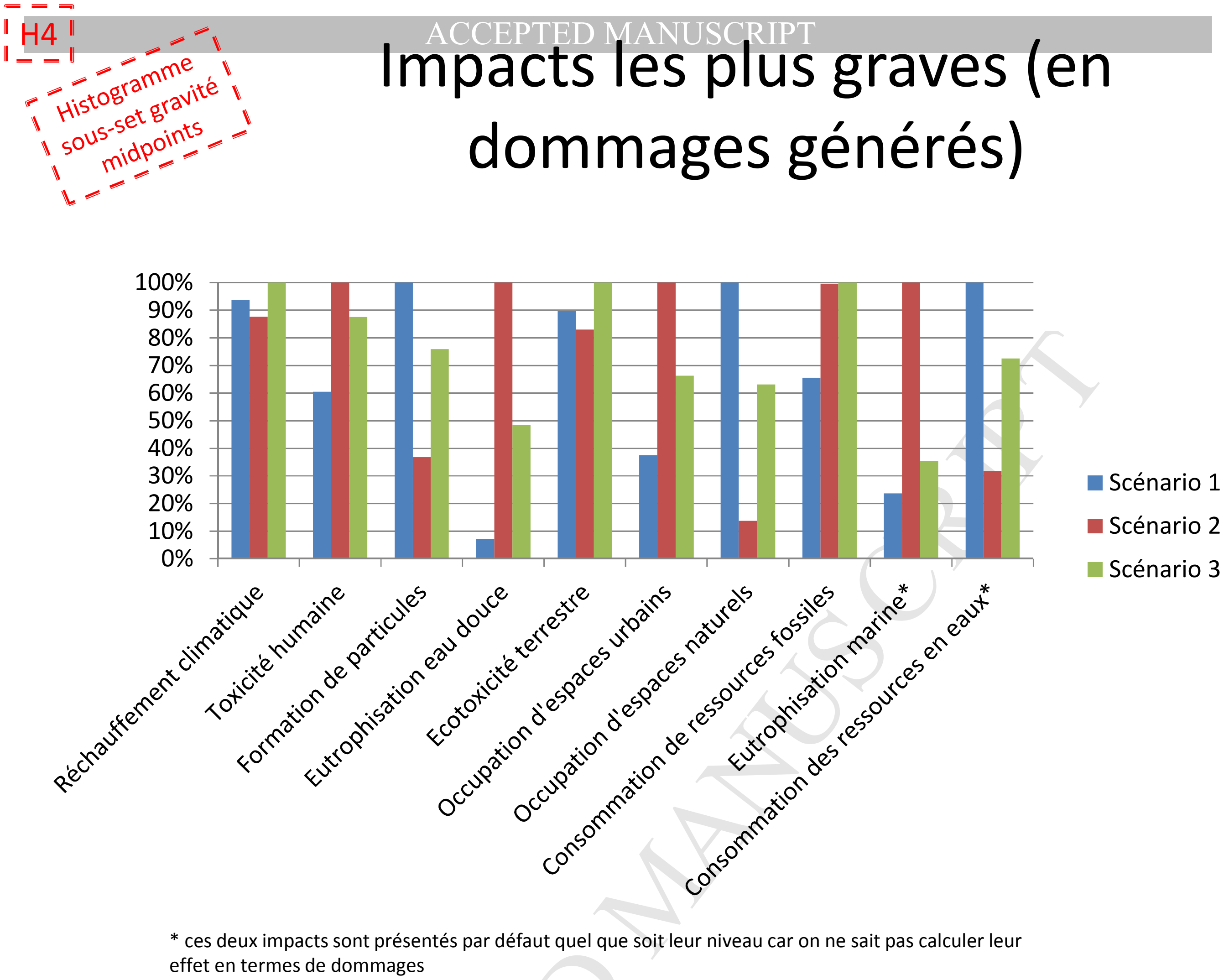


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Figure D. 5 H4 Midpoint subset histogram (severity)

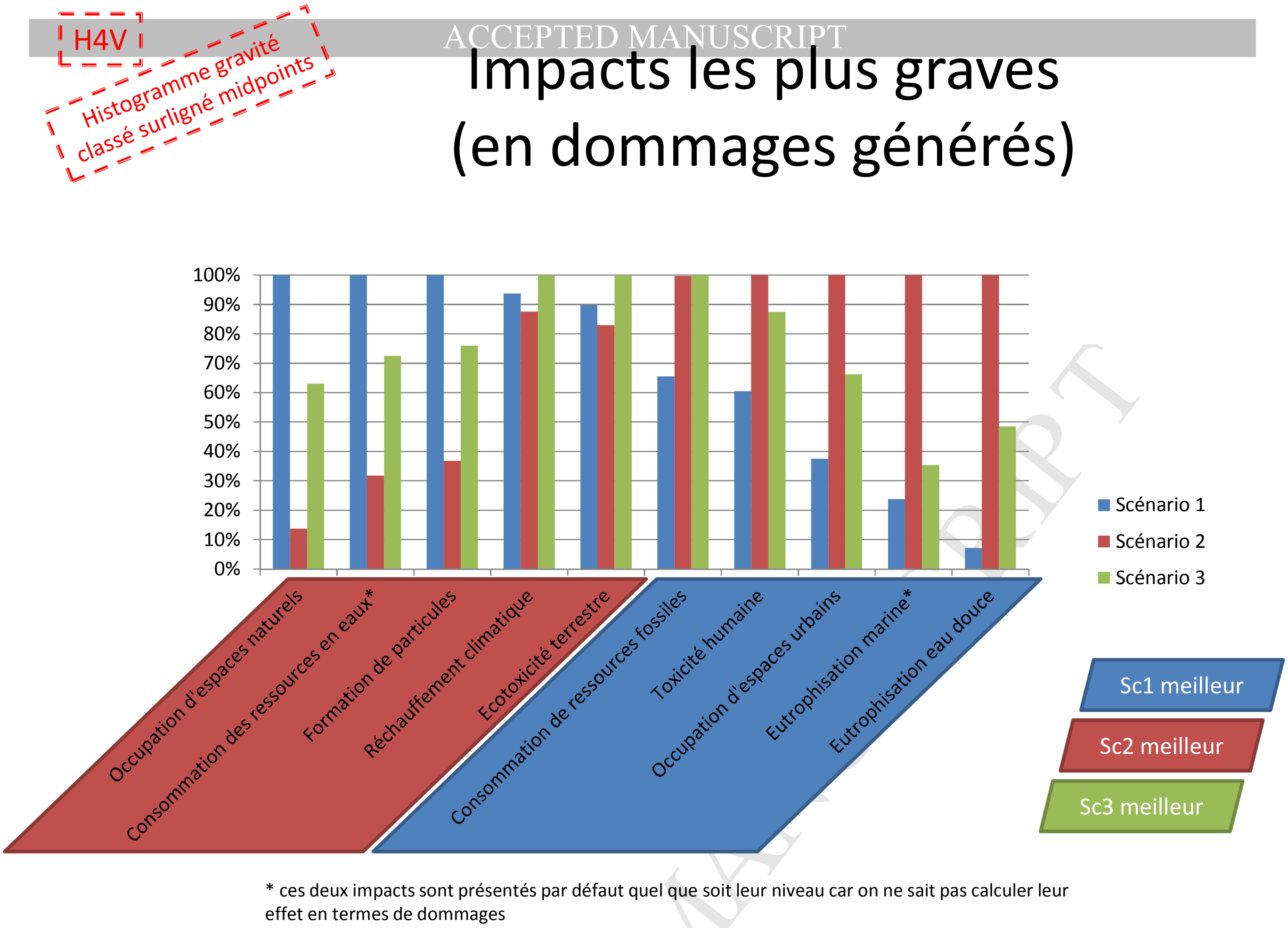
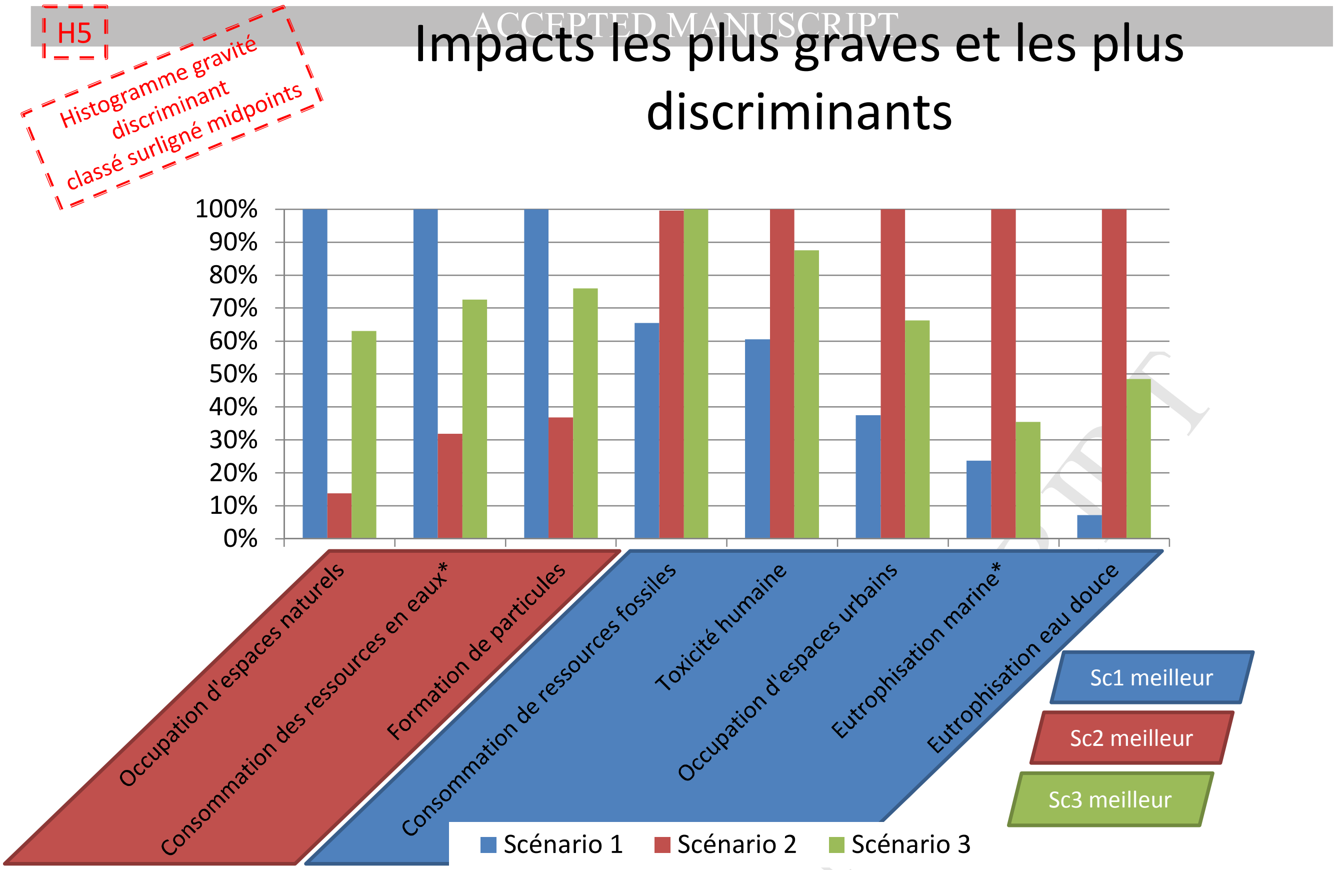


Figure D. 6 H4V Ranked and highlighted midpoint subset histogram (severity)



* ces deux impacts sont présentés par défaut quel que soit leur niveau car on ne sait pas calculer leur effet en termes de dommages

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Figure D. 7 H5 Ranked and highlighted midpoint subset histogram (severity and discriminant)

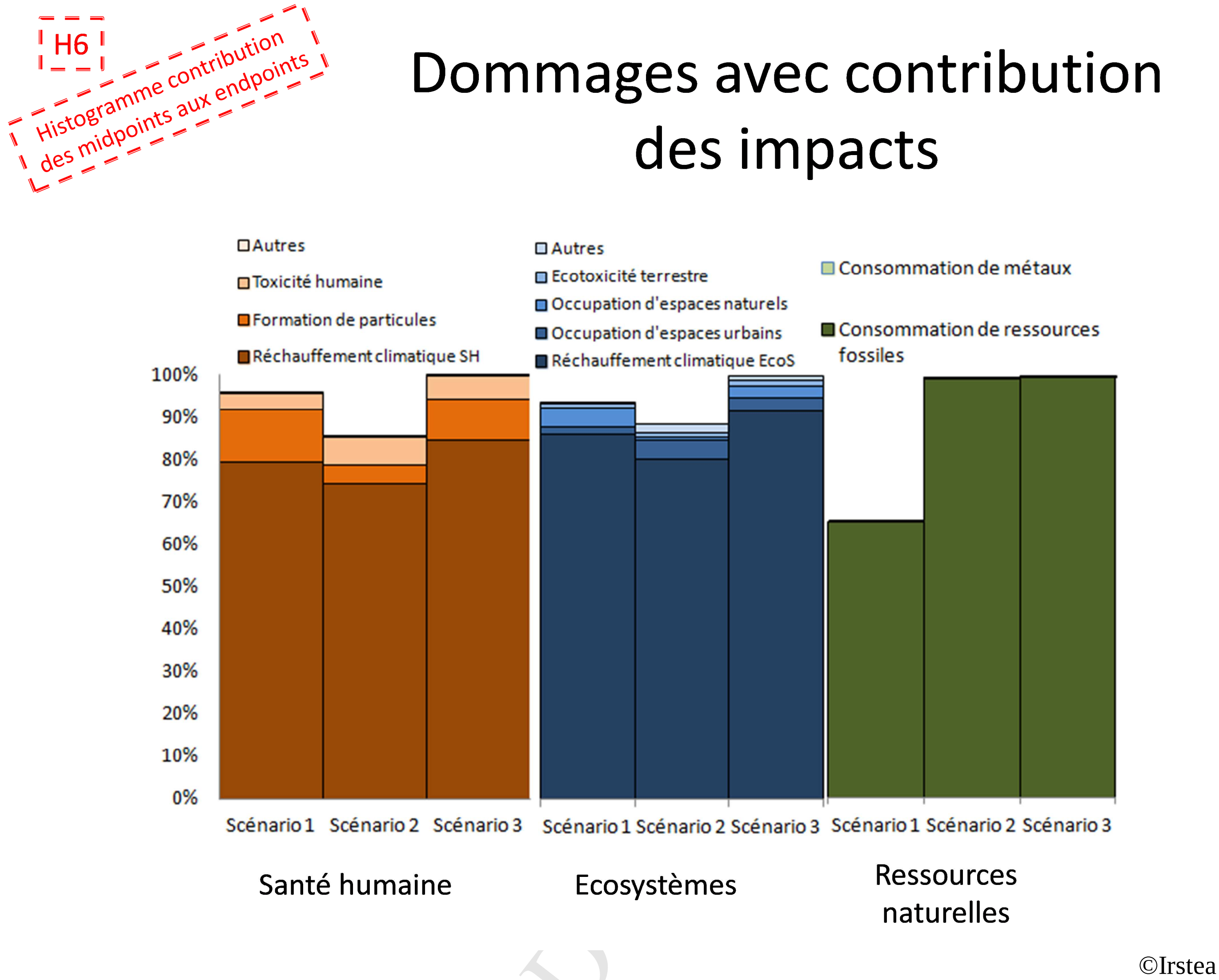

Figure D. 8 H6 Endpoint histogram with contribution of midpoints

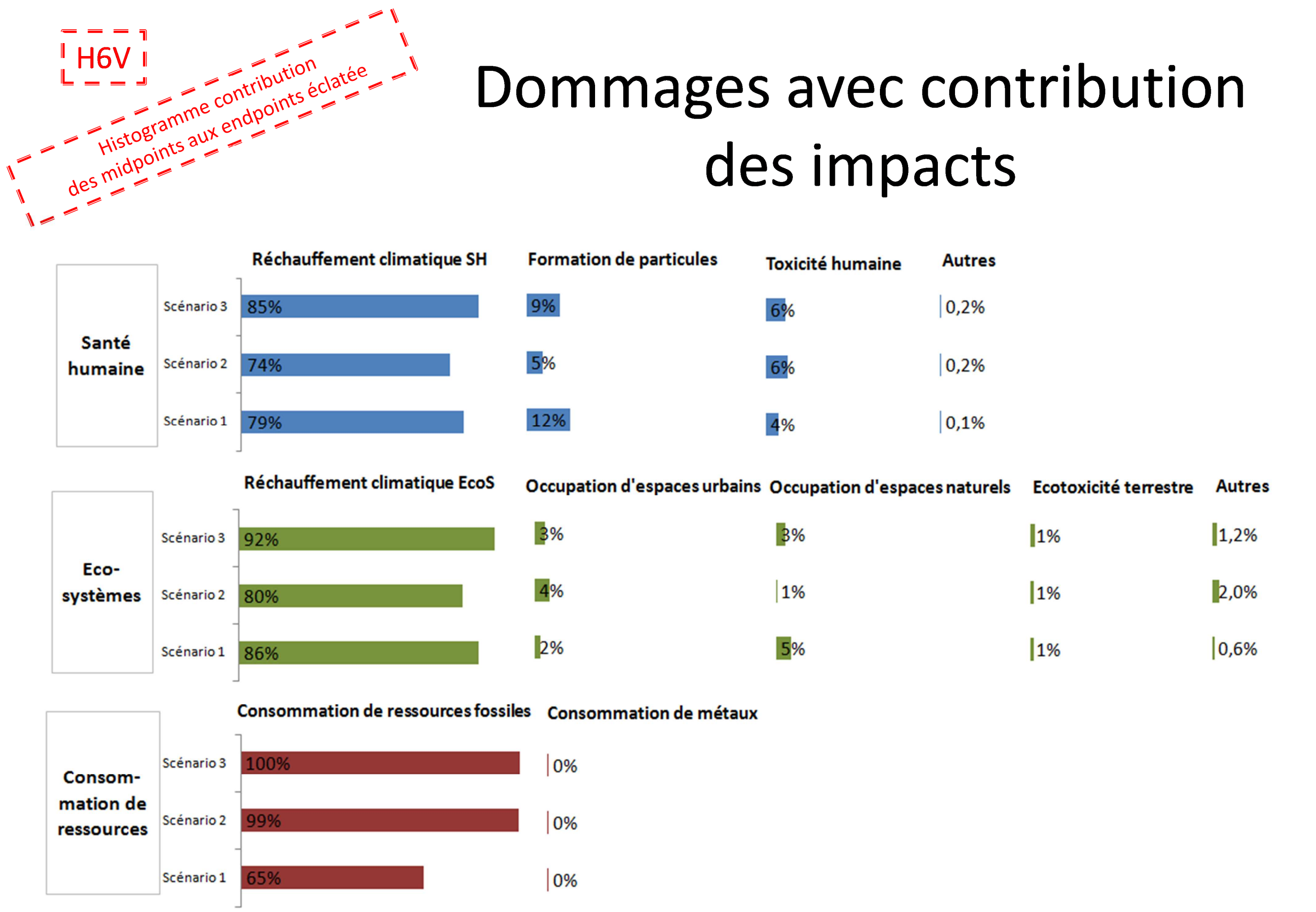

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Figure D. 9 H6V Endpoint histogram with contribution of midpoints broken down

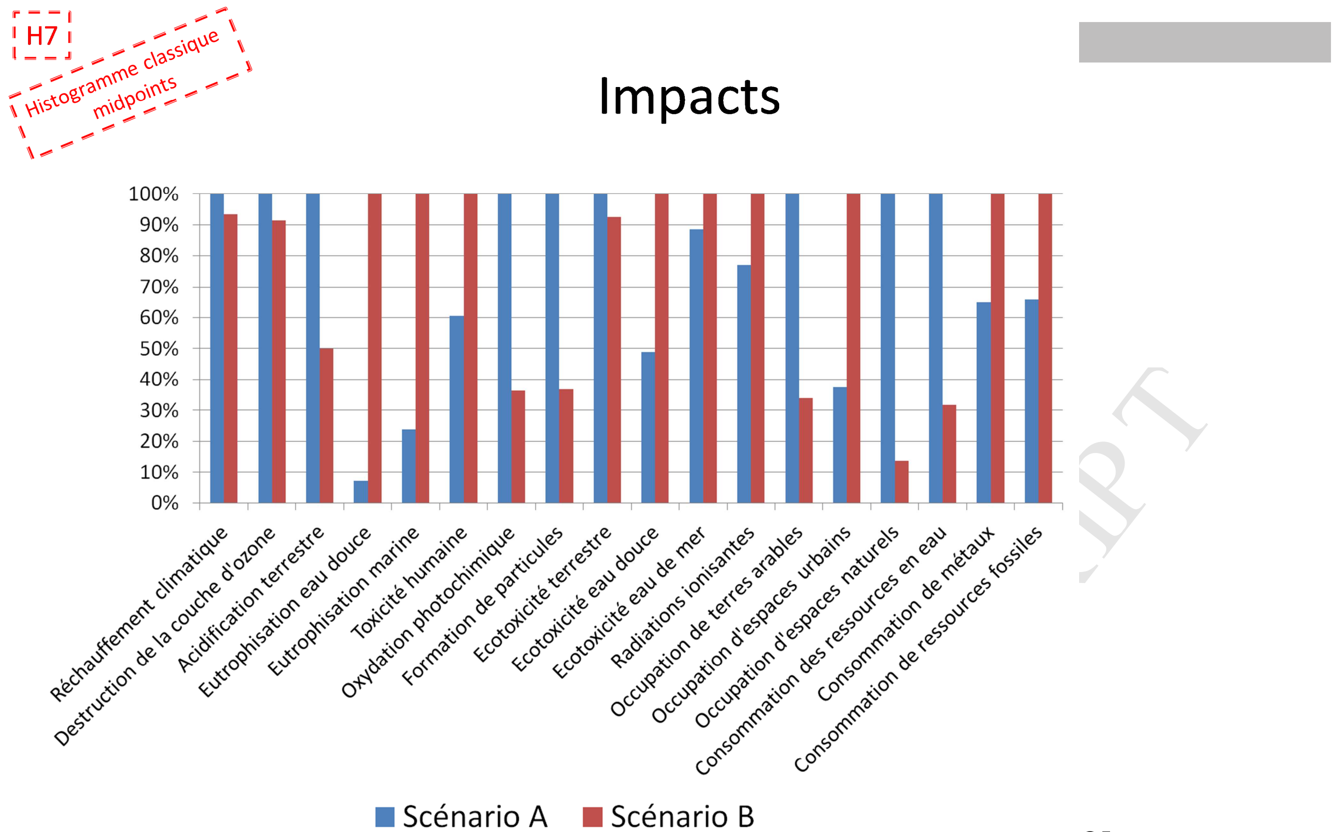

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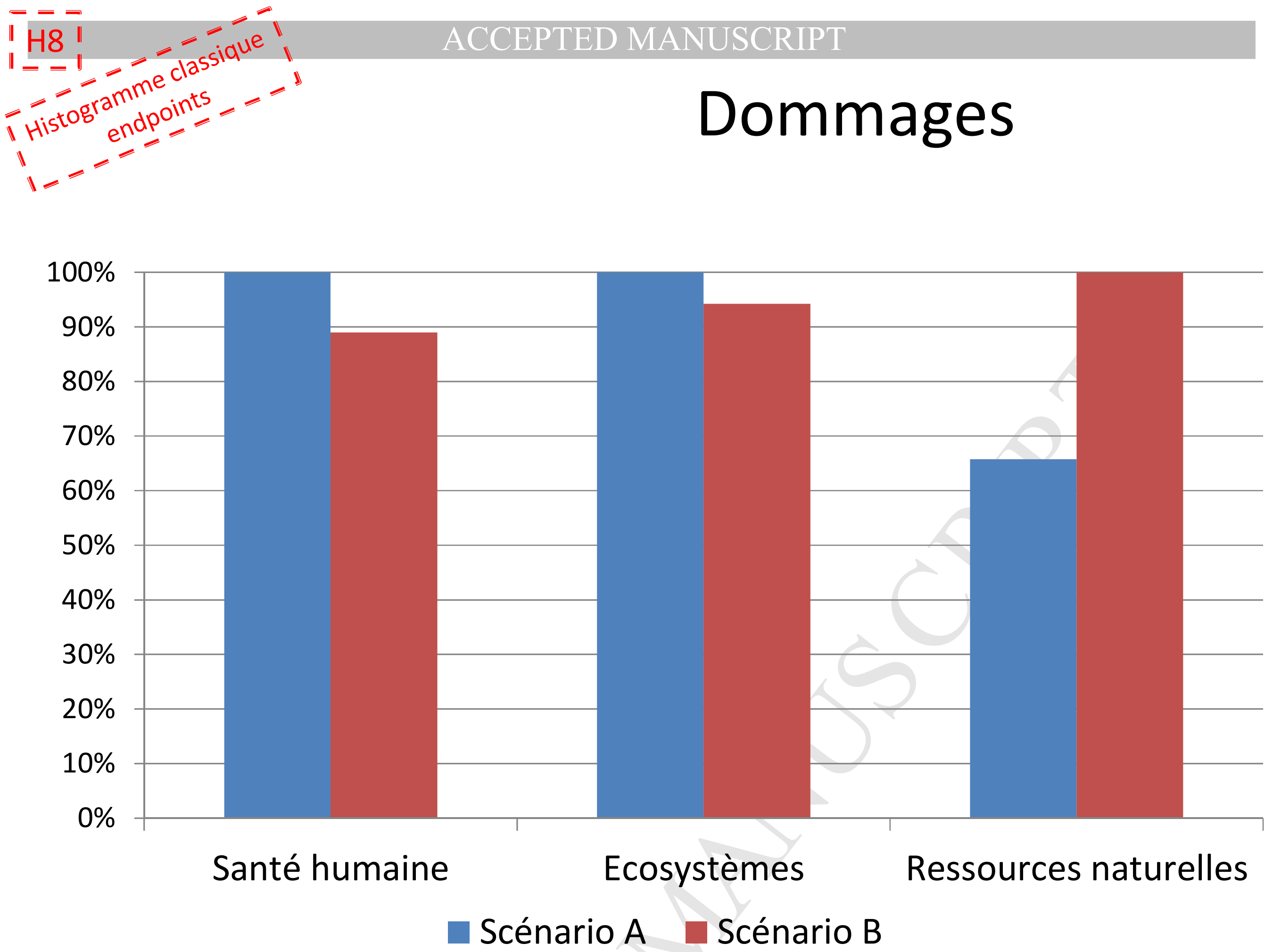
Figure D. 10 H7 Conventional midpoint histogram (2 scenarios exactly)



©Irstea

Figure D. 11 H8 Conventional endpoint histogram (2 scenarios only)

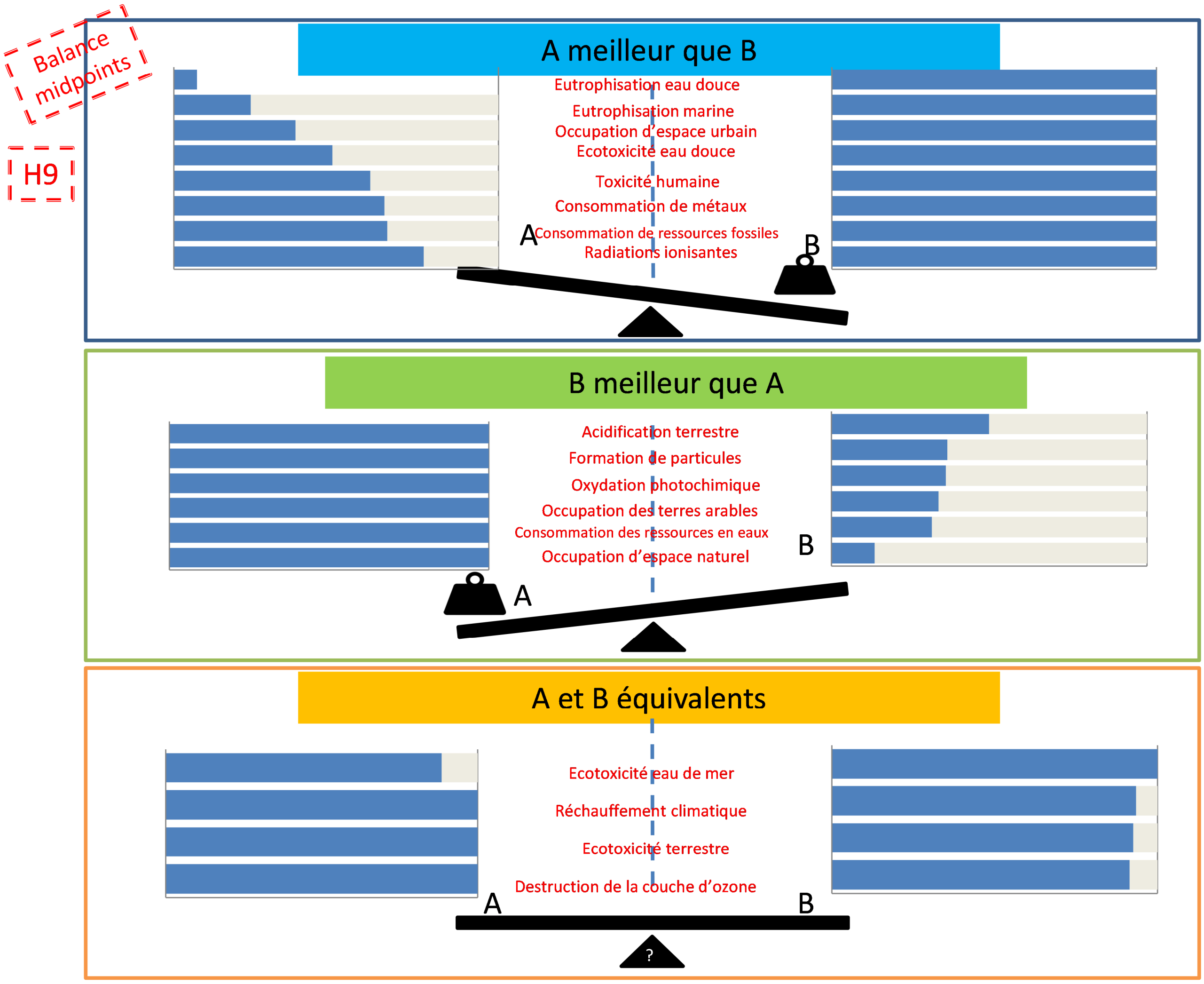


Figure D. 12 H9 Midpoint histogram on a balance

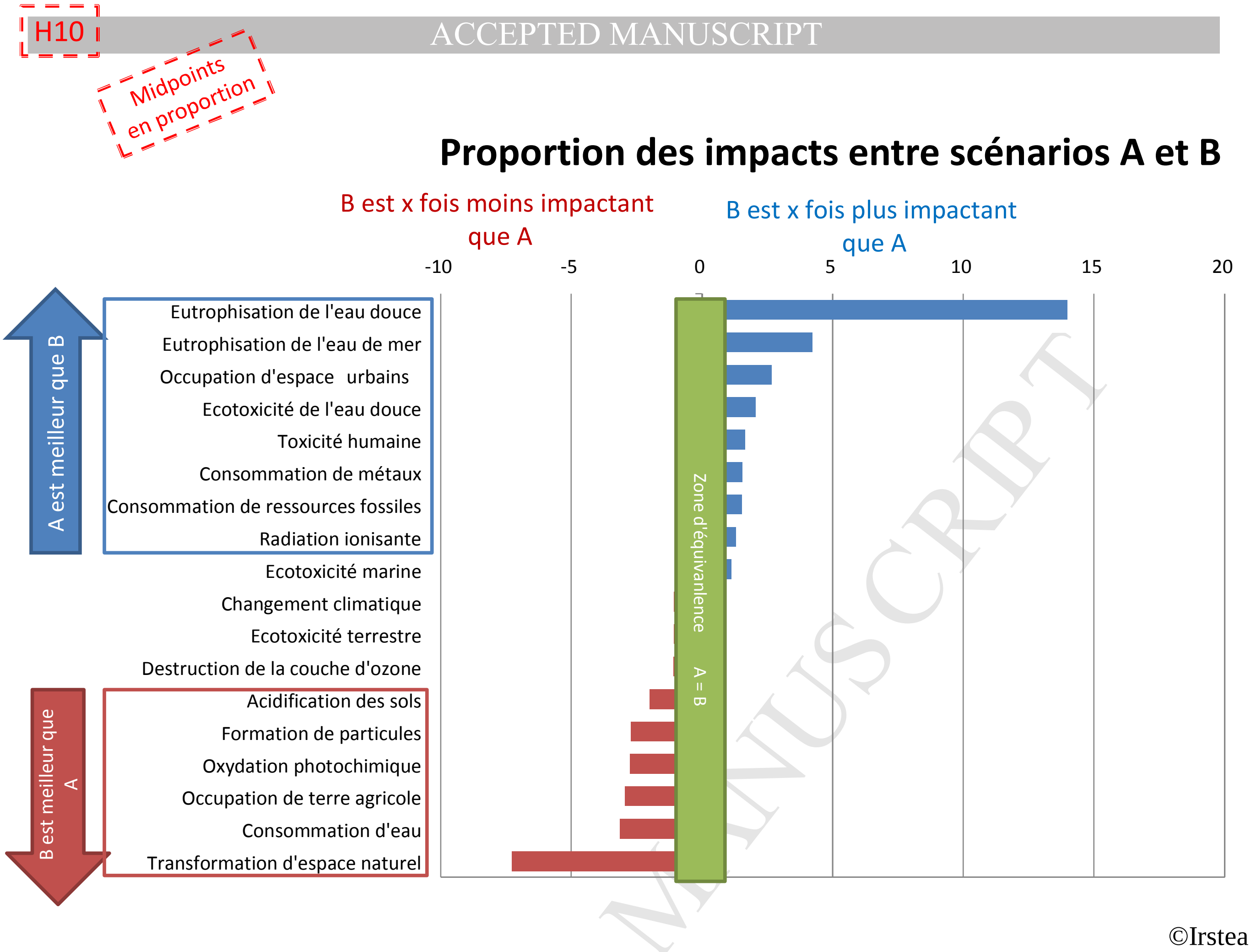


Figure D. 13 H3 H10 Midpoint histogram showing ratio between scenarios

Appendix E: Other new graphs introduced into ACV4E

These graphs were not tested directly during the experiment but are derived from the recommendations made based on the test. This is a screenshot of the version of ACV4E that was modified after the test.

Note: these graphs correspond to a dataset that is different from that of the test. The same scenarios are not involved.

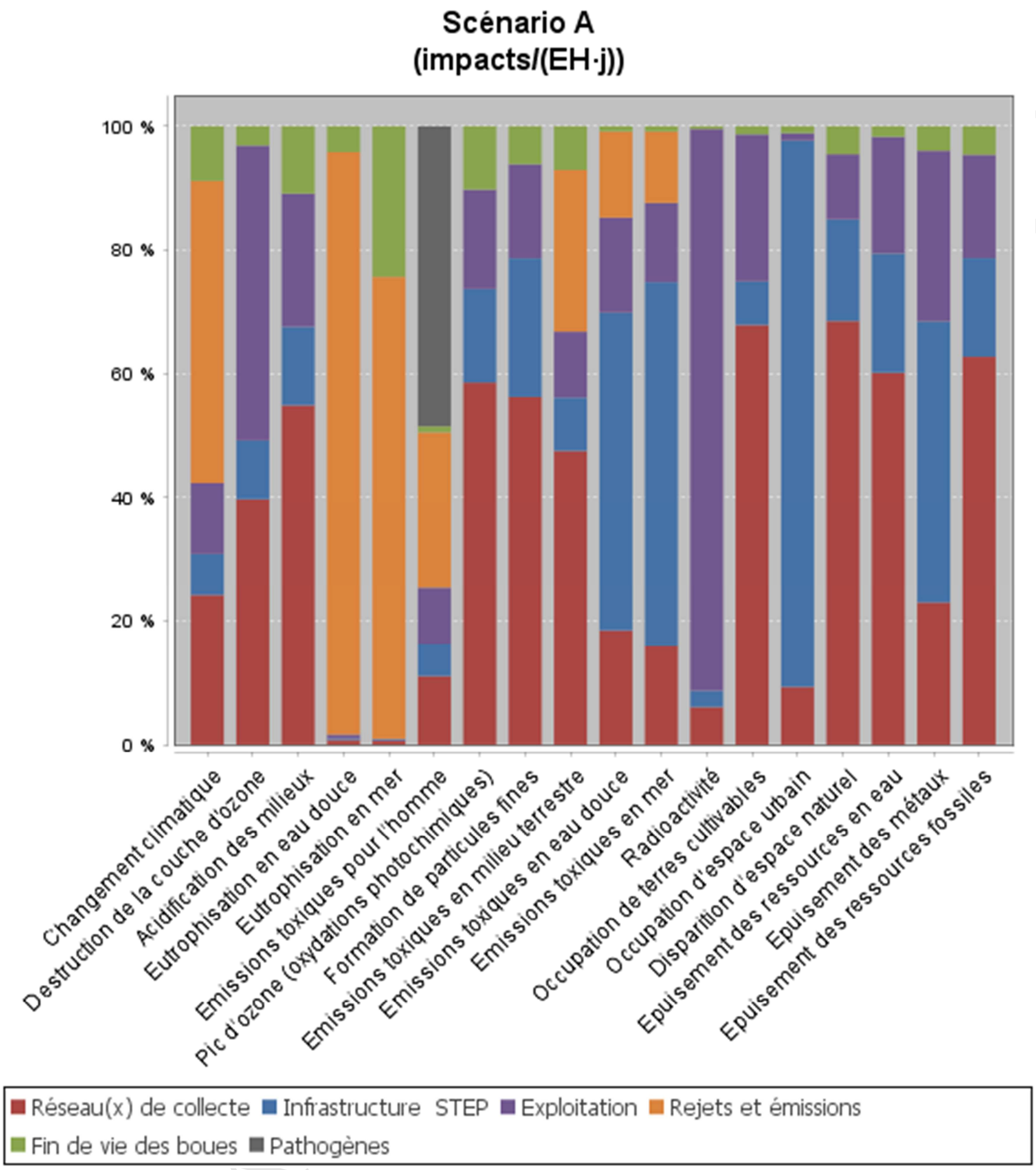


Figure E. 1 Graph [1] of the analysis of impacts' contributions (18 categories)

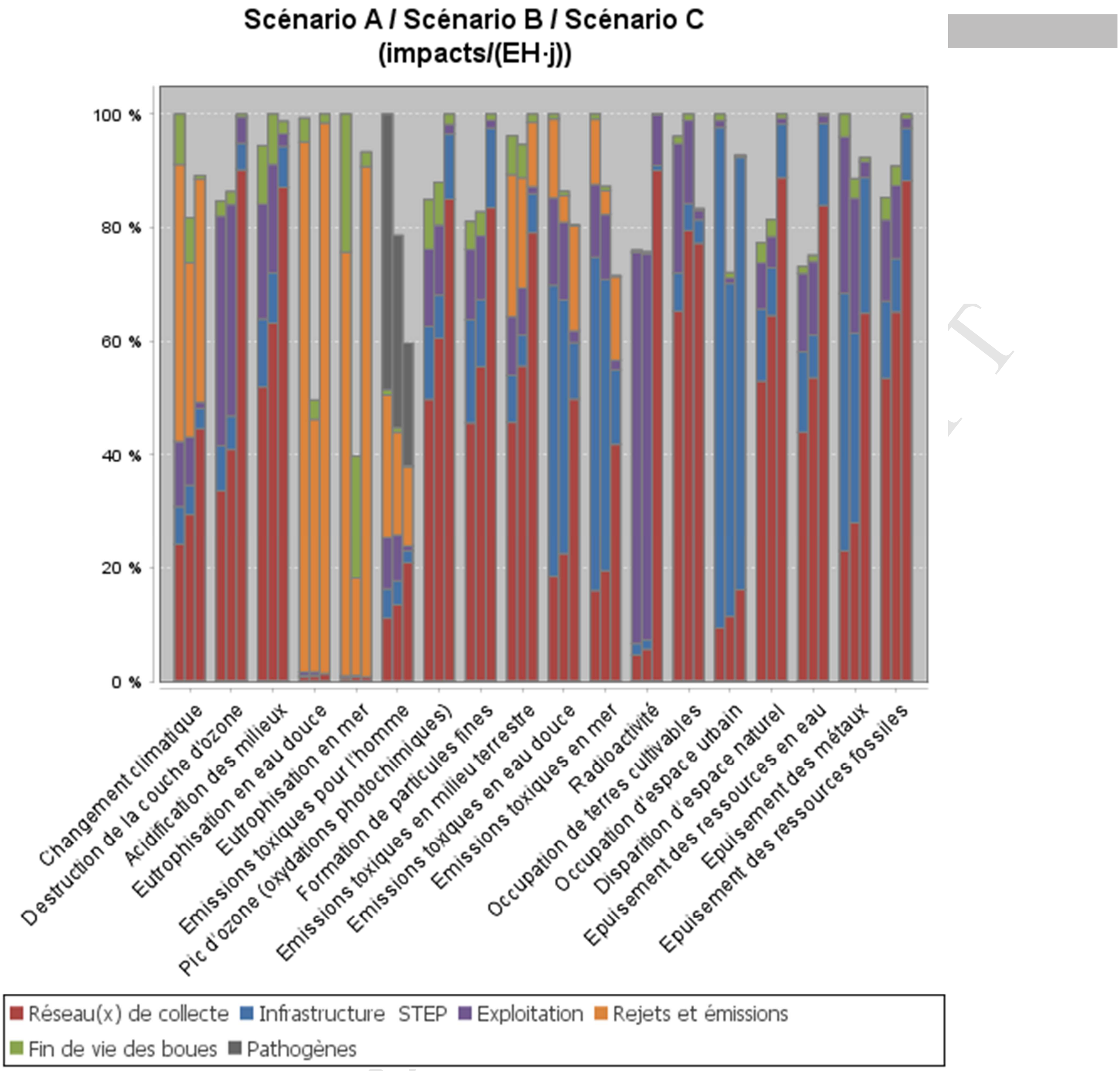


Figure E. 2 Graph [2a] Comparison Impacts (18 categories) with an analysis of contributions

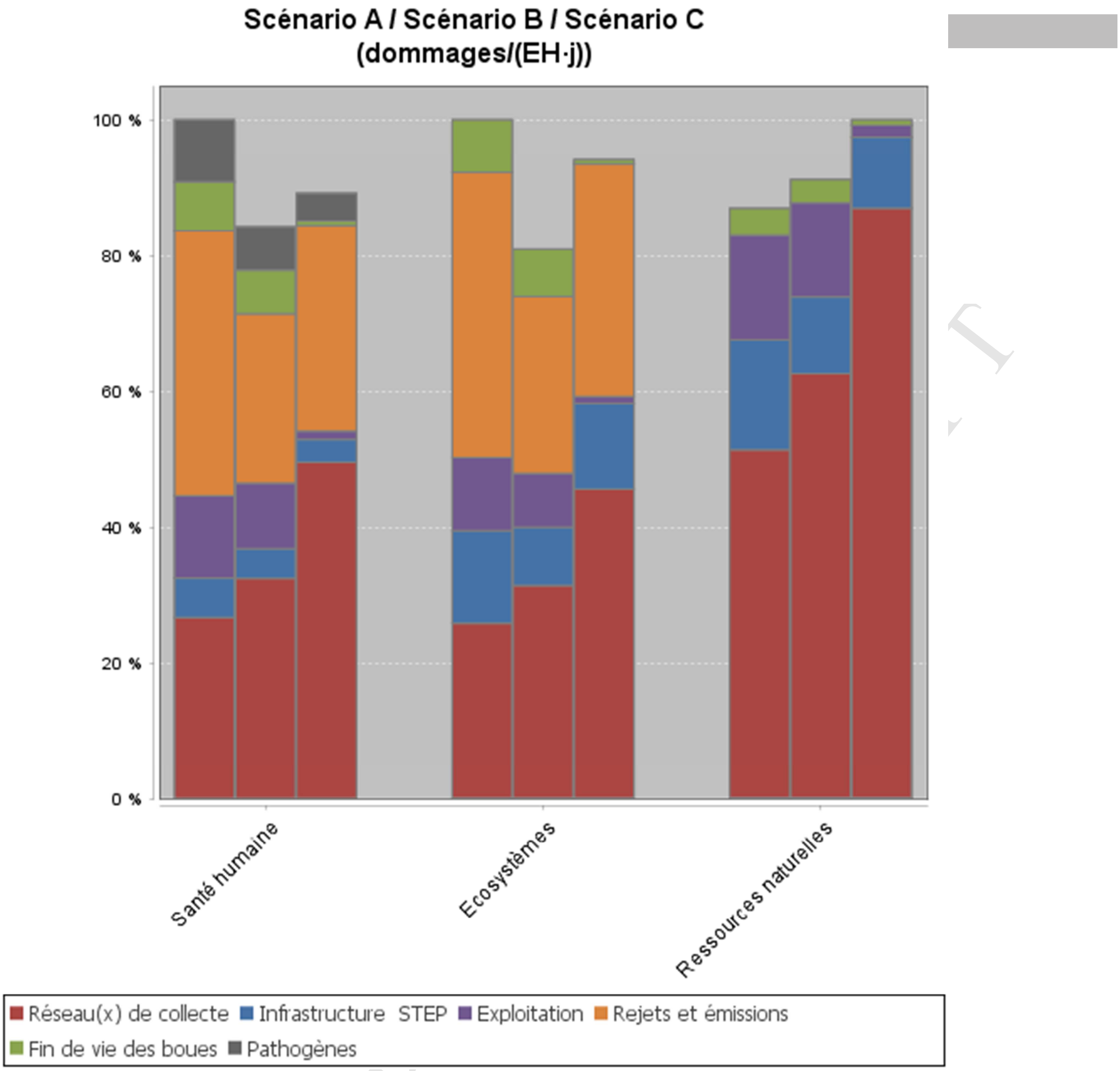


Figure E. 3 Graph [2b] Comparison Damages (3 categories) with an analysis of contributions

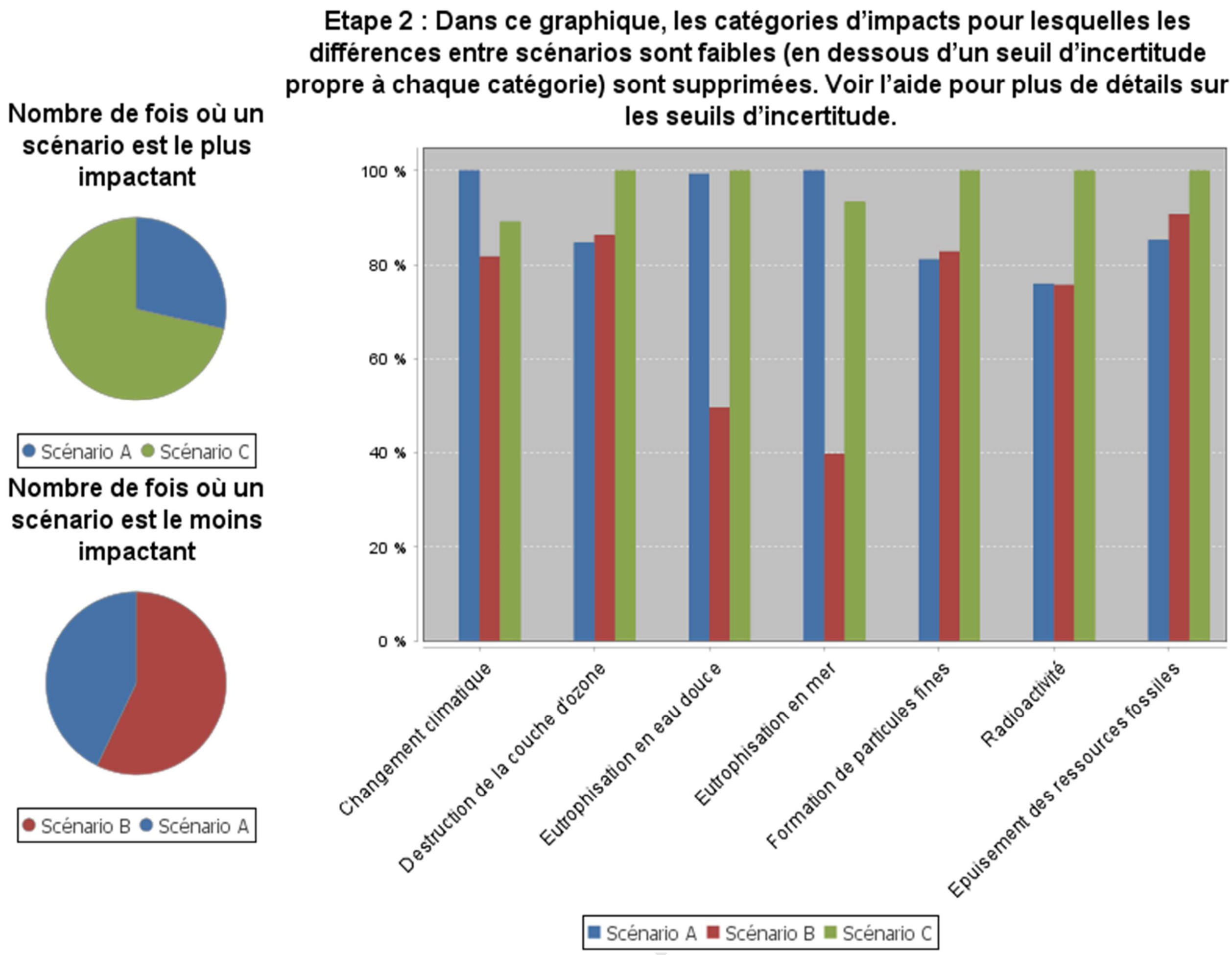


Figure E. 4 Graph [3a-ii] Graph Impact and two pie-charts qualifying the number of times a scenario was the best or worst

Appendix F: Uncertainty thresholds used to rule out criteria

Table F. 1 Uncertainty thresholds used to rule out criteria for which the differences between scenarios are non-discriminant

<table>
<tr><th>Indicator</th><th>Uncertainty threshold of results</th></tr>
<tr><td colspan="2">The 18 impact indicators (ReCiPe method)</td></tr>
<tr><td>Climate change</td><td rowspan="5">10%</td></tr>
<tr><td>Ozone depletion</td></tr>
<tr><td>Ionizing radiation</td></tr>
<tr><td>Fossil resource depletion</td></tr>
<tr><td>Particulate matter formation</td></tr>
<tr><td>Terrestrial acidification</td><td rowspan="9">30%</td></tr>
<tr><td>Freshwater eutrophication</td></tr>
<tr><td>Marine eutrophication</td></tr>
<tr><td>Photochemical oxidant formation</td></tr>
<tr><td>Agricultural land occupation</td></tr>
<tr><td>Urban land occupation</td></tr>
<tr><td>Natural land transformation</td></tr>
<tr><td>Water depletion</td></tr>
<tr><td>Fossil depletion</td></tr>
<tr><td>Human toxicity</td><td rowspan="4">30% (1)</td></tr>
<tr><td>Terrestrial ecotoxicity</td></tr>
<tr><td>Freshwater ecotoxicity</td></tr>
<tr><td>Marine ecotoxicity</td></tr>
<tr><td colspan="2">The 3 damage indicators (ReCiPe method)</td></tr>
<tr><td>Human health</td><td>20% (2)</td></tr>
<tr><td>Ecosystems</td><td>20% (2)</td></tr>
<tr><td>Natural resources</td><td>15% (2)</td></tr>
</table>

(1) *Note: when comparing systems which are more or less efficient but which generate the same types of pollutants in greater or lesser quantity, the significance threshold may be reduced, even for toxicity categories.*
(2) *The thresholds proposed for the damage indicators take into account the fact that climate change is a major contributor to damage to human health and ecosystems.*

Appendix G: Correspondence between graphs finally introduced in in ACV4E and graphs tested

Table G. 1 Correspondence between the proposed graphs (introduced in ACV4E) and the graphs tested during the experiment

Objective	Graph or procedure	For the procedures, graphs corresponding to a step	Corresponding graph in the test and/or figure illustrating the graph*
1 – Improve the operation of one wastewater treatment system	[1] Analytic graph of Impact contributions (18 categories)	-	Figure E.1**Error! Reference source not found.**
	[1a] Closer analysis of certain contributions: Details operations	-	not presented
	[1b] Closer analysis of certain contributions: Detail end of life of sludge	-	not presented
2 - Improve the operation of a group of wastewater treatment systems	[2a] Comparison **Impacts*** (18 categories) with an analysis of contributions	-	Figure E.2
	[2b] Comparison **Damages** (3 categories) with an analysis of contributions	-	Figure E.3
3 – Make investment choices between several scenarios	[3a] Comparison of **several scenarios** (>2)	[3a-i] Graph **Impacts** (18 cat.)	H1 Conventional midpoint histo (Figure D.1)
		[3a-ii] Graph **Impacts*** ((18 - x) cat.) + 2 pie-charts quantifying the number of times a scenario is the best or worst	Figure E.4
		[3a-ii-v] idem removing the worst scenarios	not presented
		[3a-iii] Graph **Impacts*** ((18 – x+y)) cat.) + 2 pie charts quantifying the number of times a scenario is the best or worst	H5 Ranked highlighted severity and discriminant midpoint subset histo (Figure D.7)
		[3a-iii-v] idem removing the worst scenarios	not presented
		[3a-iv] Graph **Damages** (3 cat.)	H2 Conventional endpoint histo (Figure D.2)
		[3a-v] Graph **Damages** ((3 - z) cat.)	not presented
		[3a-v-v] idem removing the worst scenarios	not presented
	[3b] **Simplified** comparison of **two** scenarios	[3b-i] Graph **Impacts*** in ratios (18 cat.)	H10 "Ratio" midpoint histo (Figure D.13)
		[3b-ii] Graph **Impacts*** ((18 - x) cat.)	not presented

*Reminder: The test only involved the graphs relevant for the investment choice. All of the graphs used during the test are provided in the supplementary material. The recommended version may differ slightly: especially in the order of the impacts that we suggest to regroup by area of damage (which was not done during the test).

Appendix H: Description of the three scenarios used in the test

Table H. 1 Brief description of the scenarios used for the test of the graphs

<table>
<tr><th>Scena-rios</th><th>Scenario description (1)</th><th>Functional Unit (FU)</th><th>System boundary</th><th>Inventory data sources</th></tr>
<tr><td>Sc. 1</td><td>100% centralized solution using an activated sludge (AS) WWTP (10500 inh. eq.) and connecting pipes</td><td rowspan="3">Effluents collection and treatment of an inhabitant equivalent emitted during one day (2)</td><td rowspan="3">As describe in (Risch et al., 2014) figure 2</td><td rowspan="3">See all LCI details in technical reports and publications on:</td></tr>
<tr><td>Sc. 2</td><td>100% decentralized solution using two activated sludge (AS) WWTP and a vertical flow reedbed filter (RBF) for the smallest village. No connecting pipes.</td></tr>
<tr><td>Sc. 3</td><td>A third option in which the smallest village is connected to the AS-WWTP of the 3000 inh. eq. village (pipe 2km) and the city has an autonomous AS-WWTP.</td></tr>
<tr><td colspan="5">(1) Scenarios considered concern different options for the renewal of sanitation systems of three municipalities: a small city (6500 inh. eq.), one village located 5km away (3000 inh. eq.) and a second village located 2km away (1000 inh. eq.).
(2) 1 inh. eq. d^{-1} = 60g BOD5.d^{-1} as described in detail in Risch (2014)</td></tr>
</table>

Appendix I: Criteria used for investment decision in wastewater services

In the field-experiment as reported in Guérin-Schneider et Tsanga Tabi (2017) we sought to identify the usual creteria of decision-making and the part accorded the environment when LCA is not used. This is reported in Table I.1.

Table I. 1 Criteria usually considered by local authorities in investment decisions for a wastewater treatment facility (adapted from Guérin-Schneider and Tsanga Tabi, 2017).

Criteria (level of importance in the decision*)	**Elements considered**
Regulatory obligations (+++)	- wastewater treatment performance (level of discharge into the environment) - respect of rules in terms of distance from housing
Technical dimension (+++)	- capacity to maintain wastewater treatment performance (reliability) - treatment capacity when raining (reliability) - feedback available (reliability) - degree of technicality required (simple to operate) - consistent with existing facilities (easy to operate) - innovative facility (innovation is sometimes seen as an advantage)
Economic dimension (+++)	- investment cost (++++) - operating cost (++)
Environmental and social dimensions (outside regulatory obligations) (++)	- energy consumption, carbon footprint - sludge recycling - land footprint - integration into the landscape - minimized nuisances (odor, sound...)
Administrative dimension (+)	- consultation and call for tender procedures easy to handle

*This is a qualitative assessment made on the basis of interviews and observations in French local authorities. The more "+" there are, the more important the criterion is considered in public investment decisions.